CHARACTERIZATION OF AN ACTIVE ANALYSER FOR RECOIL NEUTRON POLARIMETRY AT HIGH ENERGY

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ABSTRACT

The paper ascertained the characterizing and commissioning of an active analyser for recoil neutron polarimetry at higher energy. The active analyser is a component part of the hadron arm of the Super BigBite Spectrometer at the Jefferson Lab, United States. The active analyser consists of thirty-two detectors, an EJ200 scintillator, ET9124 photomultiplier tubes and associated read-out electronics. Initial characterizations of the response to cosmic muons as well as simulation with proton and neutron in obtaining the absolute gain, time response and their efficiencies. The absolute gain and time response obtained were 5.3x10^8 and 4.86ns, which were within operational parameters respectively; also there is variation in the signal amplitude, signal pulse and noise amplitude for each of the thirty-two detector. From the simulation results, the efficiencies of both cosmic muons and protons were around 0.8 and that of neutron were around 0.4. The variation in signal amplitude and noise level were due to interference from the background as well as loose in the optical grease between the detector and the PMT at resolution of 5ns which means that the detector can take a ray of 200mHz. Also, there are qualitative similarities between experimental and simulated results. Further study is warranted.

1. INTRODUCTION

1.1 OVERVIEW

In Virginia, the United States of America, the Thomas Jefferson National Accelerator Facility Laboratory (JLab), will be using the Super BigBite Spectrometer for an experimental program to be performed in Hall A to measure the double polarized ^{2}H $(\vec{e},e'\vec{n})$ at a four-momentum transfer $Q^2 = 4.5\ (GeV/c)^2$ utilizing common components of the Super BigBite apparatus. The Super BigBite apparatus consists of equipment to be use in implementing neutron polarimetry using charge-exchange and neutron-proton scattering to analyse the neutron-proton elastic scattering with detection of little-angle neutrons, tracking of large-angle proton and finally with charge-exchange np scattering with tracking of forward-angle protons. The device includes both an electron arm located in the BigBite spectrometer and the hadron arm that will be used for proton and neutron polarimetry, consisting of a copper block known as the active analyser (Annand 2017 and Gautam 2019)

The active analyser detector system, as well as its development and performance, entail detailed commissioning strategies with cosmic muons, neutron and proton particles. Its initial characterization with cosmic muons will aids in its finally usage with proton or neutron at the Jefferson National Accelerator Facility Laboratory, this is as results of more components been installed for the Super BigBite Spectroscopy experiment. Cosmic ray events and calibration of the detector is performed to ascertain data acquisition chains, online and offline data quality assessment, rehearsals of simulated data and streaming of events into several physics and data acquisition based on trigger output, from the internal constituents and interactions of the particle involved (Hoecker 2010).

The interaction between quarks and gluons remain a mirage for the theoretical physicists as they employed the perturbative method in understanding such process. The goal of hadron physics in understanding the strong force between quarks at high energies through Standard Model (SM), has yield little pathway by the gaps created through its employment of approximation of processes at low perturbative energies using quantum electrodynamics (QED), which is a field theory describing the interaction existing between quarks and gluons. The QCD at high energy has evolved in recent years in physics, by trying to understand the strong force existing in the nucleon beyond the standard model through the recoil neutron polarimetry at high energy (Sutton 1994)

The advent of non-perturbative theory beyond the standard model through the electromagnetic form factor has aided in the understanding of the fundamental quantity used for accurate description of the internal structure, nature and confinement of the hadron, which is an essential aspect of physics through which scattering processes are studied. The form factor is used in validating the theories between perturbative and non-perturbative theories such as the standard model, which uses mathematical tools in predicting the outcome of an event, as well as the quantum chromodynamics (QCD), and the difficulty associated with separation of electric and magnetic form factor using the Rosenbluth. The use of form factor in describing the inter-relationship between the experiment and theory, which provides intuitive understanding of the electric due to charge and magnetic due to magnetization from the angular dependence of the scattering cross section at constant four-momentum transfer. Several experimental results have previously been published about the significant contributions of different nucleon form factors in understanding the internal structure and nature of the hadronic composition of quarks and gluons, through the quasi-free electron-neutron kinematics. The kinematic region of the neutron is still unexplored in both perturbative and non-perturbative behaviour (Annand 2017 and Sutton 1994)

Recoil neutron polarimetry is use in extracting the ratio of neutron electromagnetic form factor at high energy and four-momentum transfer using the active analyser from electron beam with high luminosity and polarization, though, neutron polarimetry depends on the spin-orbit interaction of an incident nucleon with a target nucleus at azimuthal modulation of scattering cross section (Annand 2017).

The use of cosmic muons for information acquisition or data is aligned to almost all detectors, relative to each another for initial geometry and other detector characterization variables such as position, particle types, energy, time response, front-end, back-end electronics, trigger, gain and signal of the detecting particles (Hoecker 2010).

This experiment in Hall A, using the Super BigBite apparatus is aimed at finding an answer to some critical aspect associated with an np-pn charge-exchange reaction such as the analysing power of the particles as well as the rate of such reaction using Super BigBite apparatus. Answering these questions will require a powerful detector in analysing such reaction variables, this led to the development of this active analyser to be used in hadron arm of the super BigBite for recoil neutron polarimetry in obtaining data and measurement at the highest Q^2 ever (Annand 2017).

The understanding of the nature of quark confinement through the spatial distribution and the characterization of the structure of the nucleon has been a central issue for a nuclear and hadronic physicist. The small transverse distance scales in quark and the actual quark-gluon interaction through the knowledge of quantum chromo-dynamics (QCD) field theory has limits the theoretical physicist understanding about the characterization and spatial distribution of charge in the nucleon through their perturbative method (Annand 2017 and Perdrisat et al 2008).

With the active analyser, neutron from a target source will be accelerated and polarized to become a proton. These protons produced will then be moderated along the hadron arm where scientists can use them for other research purposes such as in answering some critical aspects associated with an np-pn charge-exchange reaction as well as in analysing power of the particles, the rate of such reaction, which all requires a powerful detector in analysing such reaction variables, this led to the development of this active analyser to be used in hadron arm of the super BigBite for recoil neutron polarimetry in obtaining data and measurement at the highest Q^2 ever (Annand 2017 and Wingham 2008).

This work is divided into three parts: firstly, commission an active analyser with cosmic muons, through the measurement of each of the thirty two detector operational parameters such as signal amplitude, time response, noise amplitude, finding the optimum high voltage (HV) settings as well as characterizing the variation in amplitude and time for signals along the length of the active analyser (End, Middle and PMT). Secondly, simulation with cosmic muons to ascertain the performance of the detector using other particles such as proton and neutron, by comparing the simulated detector measurement agrees with experimental data along the length of the detector, as well as using the simulation and experimental data measurement to calculate absolute gain and time response of PMT. Thirdly, measurement of detector response to high energy nucleons, through the determination of amplitude spectrum and efficiency for protons and neutrons.

2 BACKGROUND AND MOTIVATION

2.1 NEUTRON

Neutron is electrically neutral with no electric charge, it cannot therefore interacts hadronically with electrons in matter to cause ionization through the Coulomb interactions as such neutron passes through thing, and thereby having no any real effects on atomic electrons, as the nuclear particle is virtually invisible to neutrons, which is equally applicable to proton as well, since both electron and proton have opposite charge as compared with neutron which is basically neutral, as the chance of neutron interacting with matter is firmly based on the energy at which the neutron is scattered (Jalgen 2017).

2.2 RECOIL NEUTRON POLARIMETRY

Several experiments have been performed to measure / through the polarization of recoil neutron from the scattering of the polarized electron. Some of these experiments include those at MIT-Bates were Proof-of-Principle measurement was taken, as well as more accurate results from Mainz experiment and equally that of JLab, were the Q^2 of all these experiment measurements does not exceed 1.45 $(GeV/c)^2$ (Annand 2017).

Neutron electromagnetic form factor has shown an entirely different analysis as compared with proton, especially at $Q^2 > 3.4$ $(GeV/c)^2$ where no previous measurement of neutron EMFF has ever reached such value, this is attributed to difficulty and technicality associated with analysis involving neutron, it also requires the use of quasi-free scattering from light nuclei to obtain adequate information about the EMFF of neutron (Annand 2015).

Polarized observables are essential in revealing the contributing processes involving nucleon elastic form factor measurement through amplitudes contribution as compared to one-photon exchange reaction in the Rosenbluth separation experiment, as nucleon measurement in terms of Q^2 are still lagging proton measurement (Annand 2015 and Annand 2010).

2.3 MOTIVATION BEHIND THIS WORK

The purpose of this work is to provide a better understanding of the response of an active analyser (detector) for recoil neutron polarimetry at high energy by performing the initial characterization of the detector (active analyser) using cosmic-ray muons. An initial high voltage scan was done for the whole thirty-two (32) detectors which sum up the active analyser to ascertain if all the detectors were working properly. The active analyser which has been assembled at the University of Glasgow by the nuclear physics group will be commissioned to be used in Thomas Jefferson National Accelerator Facility where it tries to find the answers to some of the most challenging questions regarding nucleus of an atom. The active analyser will be used in measuring the highest ever four-momentum transfer for neutron through recoil polarimetry.

3. MATERIALS AND EXPERIMENTAL METHODS

3.1 SCINTILLATORS

A wide range of scintillator materials has been used for scientific and other purposes in research institutions; such objectives include ionizing radiation detection and spectroscopy. Different materials have been used in making scintillator, such as gaseous material like helium (^{3}He) used in neutron detection. A scintillator is a detector material, which converts ionizing radiation with high penetrating energy to visible light. The scintillation detector is used for producing large light output in the visible spectrum range (Cheol 2017, Jalgen 2017, and Lecoq 2020)

The scintillator used in this experimental measurement is the Ej-200, which is due to its high sensitivity as well as signal uniformity during operational data acquisition. It has long optical attenuation length and fast timing response, which is inherently useful in determining the time-of-flight of a detecting system. The signal amplitude has almost a Gaussian distribution against its wavelength (Tkaczyk 2018).

3.2 PHOTOMULTIPLIER TUBES (PMT)

The PMT is used for the amplification of the signal from the incoming radiation, which is then converted into photoelectron and amplified because of interaction with dynode, the signal is read out as pulse at the anode, and it is proportional to the energy of the incoming photon.

The PMT used in this experimental data acquisition is the ET9124, used in measuring the signal amplification from the cosmic muons, it converts the photons into curved light with time resolution of 0.15ns, having an optical trade off performance, coupled with its negative high voltage biases, it then produces low gain performance and high linearity over wide dynamic range (Tkaczyk 2018 and Annand 2018)

3.4 ACTIVE ANALYSER

The active analyser is parts of the main components of the neutron polarimeter. It is mainly constructed with materials with high efficiency for proton and neutron polarization; the construction materials include Carbon (C), Aluminium (Al), iron, copper, tungsten, and lead. Copper is mostly the best material for the passive component for the charge-exchange reaction due to its high number of protons per unit volume whereas tungsten is the best for the active component in term of proton and neutron density. The active analyser is used for polarization of neutron in the super BigBite spectroscopy experiment in JLab (Annand 2017).

The active analyser is a 4x8 array of 40x40x250mm EJ200 scintillator which was built by the Nuclear physics group of University of Glasgow United Kingdom with ET9124 photomultiplier tubes, which was tested and commissioned using cosmic ray muons. It consists of 32,2cmx11cmx100cm plastic scintillator.

4. EXPERIMENTAL SETUP

The measurement was performed at the Nuclear physics group Lab of the School of Physics and Astronomy, University of Glasgow. The apparatus used for this measurement provides well defined mono-energetic cosmic muons from the surrounding environment.

The experimental arrangement in the laboratory is shown in figure 8, we utilized a mono-energetic cosmic muon at 50.0ns/div., 20.0GS/s, 50.0Ps/pt, 112.0mV/div and 200.0mV/div for channel 1 and channel two respectively at 50 (ohms) on Tektronix oscilloscope for signal amplification purpose. The triggered detector was placed 2m above the active analyser in three different positions, which acquires the signal pulse and distribution at three different locations along the detector labelled as PMT, Middle and End respectively.

4.1. TRIGGER AND DATA ACQUISITION

The trigger in this experiment involves or serves as a function of trigger detector response to collision events, whenever there is a signal acquisition in the active analyser and the trigger detector. The acquisition of signal from the trigger detector is amplified and registered as a signal using the coincidence unit of either AND/OR, which merely allows the digital oscilloscope to record the photon as a signal. The data acquisition functioned by the collection of signal information from the detector for offline analysis.

5. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental data were measured using cosmic muons at an initial high voltage scan for the whole thirty-two-detectors, where the signal amplitude distribution as a function of applied voltage at 800V shows variation in the signal output, with some detectors showing low signal amplitude, high signal amplitude and mostly average signal amplitude as depicted in figure 11. Some detector with low and high signal amplitude was measured again at a varied high voltage scan to see the effects of change in voltage, it was found out that, there is a Gaussian distribution in the signal amplitude as a function of change in the high voltage supply across both the low, average and high signal amplitude detector.

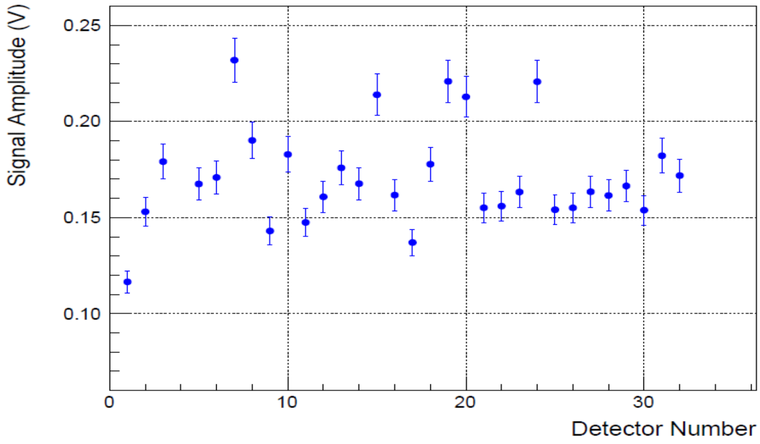

Figure 1: The plots from the data of the signal amplitude of the thirty-two-detector used in the ongoing analyser construction as a function of signal (V) against the detector number

Figure 1 above shows the mean value of signal amplitude for each of the thirty-two (32) detector used in the active analyser. From the plot, it could be seen that almost all the detector has signal value within the same range, as such, it shows that they can be used for the characterization purpose of the active analyser and subsequently suitable for used in the hadron arm of the Super BigBite spectroscopy experiment.

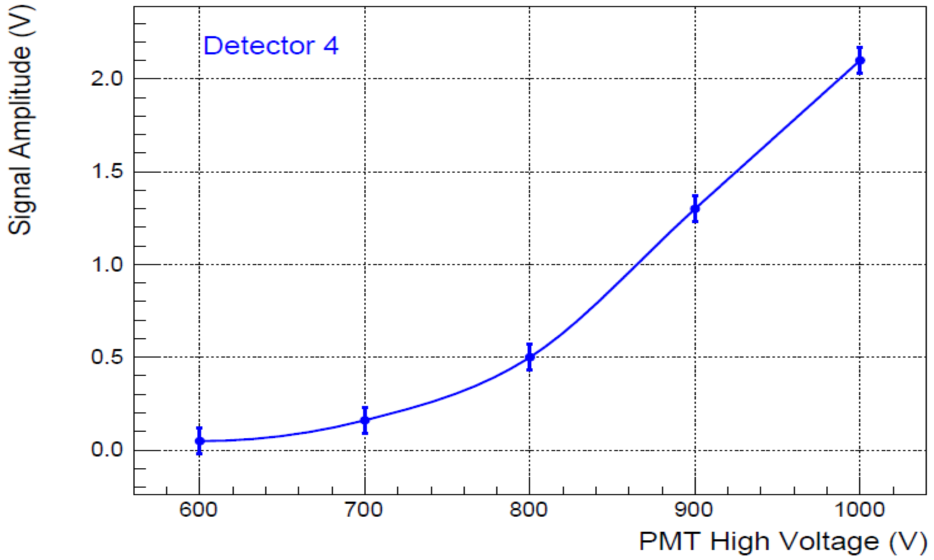

Figure 2: Plots of one of the detectors with low signal amplitude as a function of varying high voltage

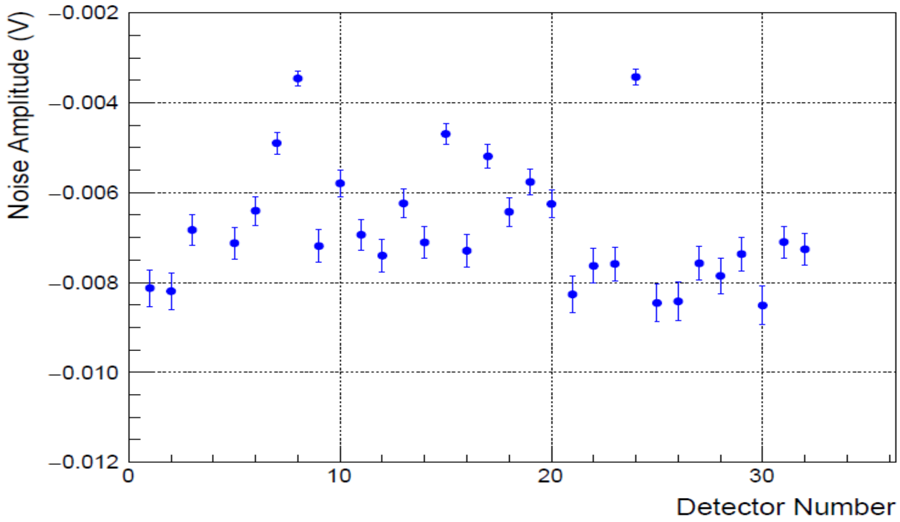

Figure 3: Noise distribution as a function of varying detector number the active analyser.

Figure 3 above illustrates the distribution of noise across the thirty-two-detector used in the active analyser, the mean noise amplitude is within the same mean value, the effect of noise can be seen from the signal generated from each of the corresponding detector number, the less the noise amplitude, the better the signal generated for each of the detectors.

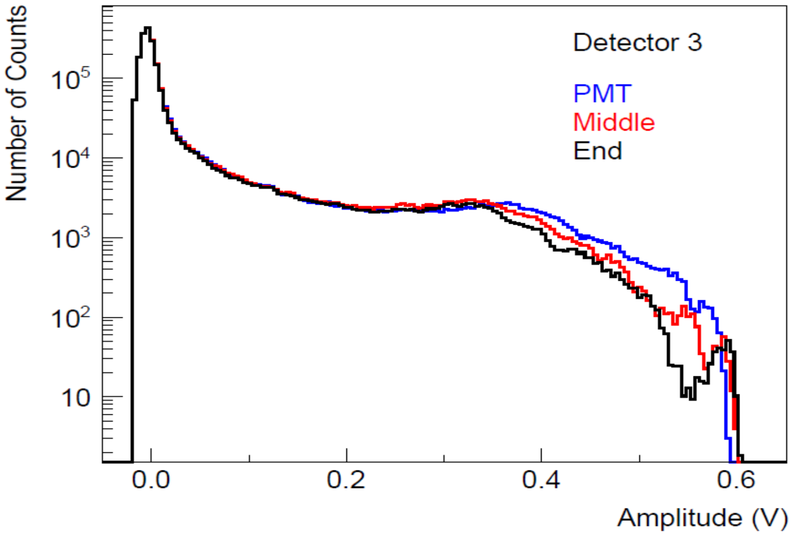

Figure 4: Triggered detector with detector number 3 showing the signal amplitude at a different position within the active analyser

In figure 4 above, a triggered detector was coupled with the active analyser to see the effect of signal generation at different locations within the active analyser, the signal generated at a different location is within the same mean value, and as such, the detector shows similar characteristics using un-triggered and triggered detector measurement.

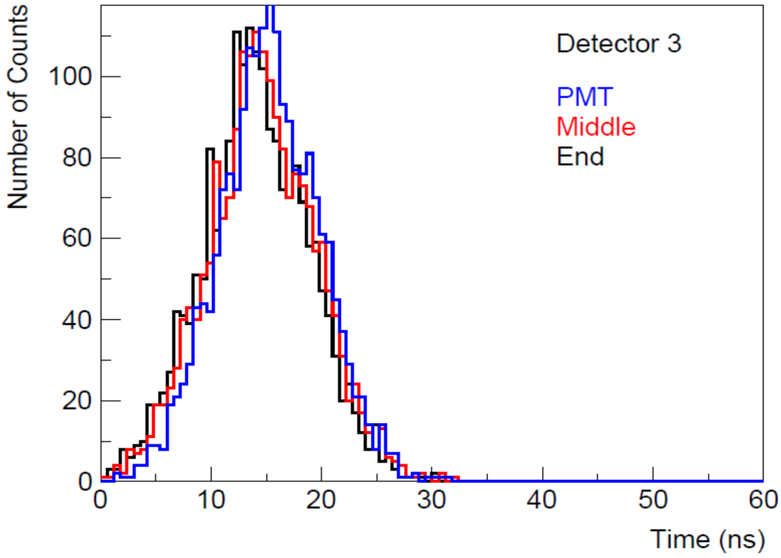

Figure 5: The signal pulse of a selected detector along different location within the active analyser as a function time resolution

Figure 5 above illustrates the signal pulse of a selected detector along different location within the active analyser as a function time chosen at random from the other thirty-two (32), to show the time resolution of the signal amplitude at different position of the active analyser, the position of the active analyser were segmented into three different part such as PMT, Middle and End.

5.1 SIMULATION RESULTS AND DISCUSSION

The used of Monte Carlo simulation method has been employed in virtually all components of experimental particles physics measurement, from detector geometry concept, design, optimization, and data analysis for the interpretation of particles through matter (Maria 2012, Buller 2013 and Moralles et al 2009)

In this experiment, we employed the GEANT4 simulation toolkit in obtaining the number of cosmic muons hitting our detector along the length of the detector (active analyser) at different locations of End, Middle and PMT, as well as the standard deviation for measuring the time response of the detector signal input from the signal output.

5.3 SIMULATION RESULTS AND DISCUSSION

When analysing the outputs of the simulations, we exclusively looked at the number of optical photons, which is the total number of cosmic muons hitting the detector or the energy contribution for a given event or detector. This number of hits is termed as $N_{photons.}$ It is used in calculating the gain of the detector. Subsequently, the standard deviation or the RMS for time response as well for the detector, which is the time required for a change in detector signal input to the output signal of the detector. The values for both the number of signal hits and the time response of the detector in respect to signal change are normalised to an estimated value not for the calibrated data due to simulation yield in the detector construction geometry. Table 1 shows the values for $N_{photons}$ and standard deviation at a different position along the active analyser.

Table 1: showing the values of different location along the active analyser

Position	$N_{photons}$	
	Real	Normalized
End	73.79	9250
Middle	75.08	9375
PMT	80.25	10000

From table 1 above, the number of photons hitting the detector is much more at the other end of the detector where the PMT is situated as compared with the other two position which are the middle and the end part of the active analyser.

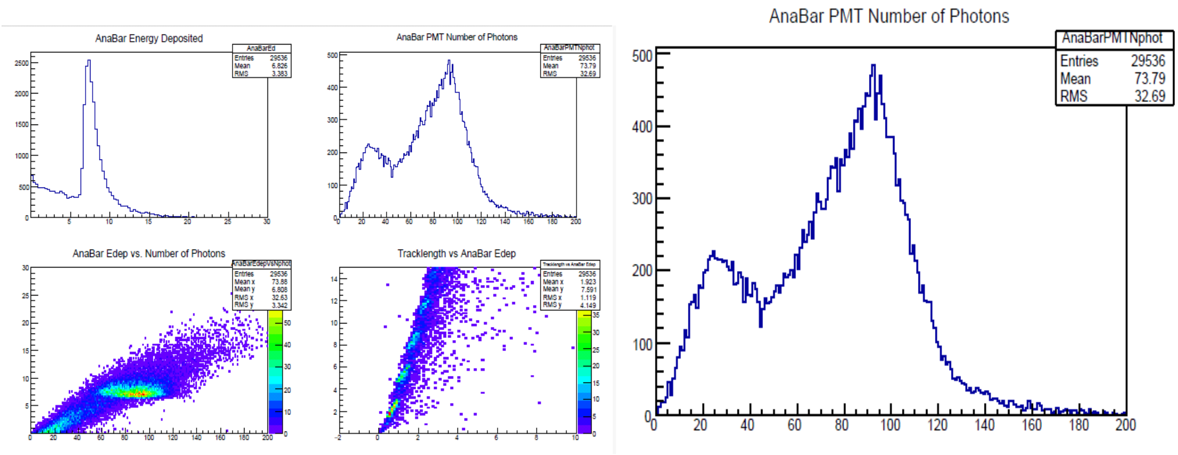

Figure 6: mean value of optical photons hitting the detector from the simulation data as a function of number of counts

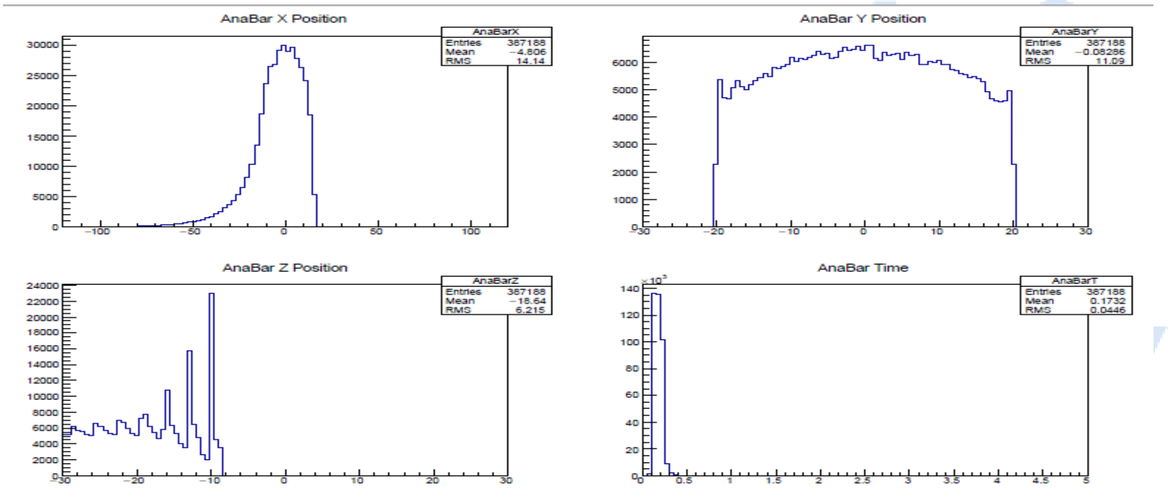

Figure 7: The RMS or standard deviation measurement of the simulated data from the AnaBar detector used in the simulation of cosmic muons measurement as a function of the time response of the detector

Our main result measurement centered on the gain and time response of the detector used in the active analyser; this can be calculated as follows:

$$Q = IT \quad (1)$$

$$Q = (\ N_{photons} * E_{quantum}\ ) * e * G \qquad (2)$$

Where

I = current

V = voltage

R = resistance

$N_{photons}$ = mean value of optical photons hitting the detector from the simulation data in figure 20 above.

$E_{quantum}$ = Quantum efficiency of the EJ200 PMT at 10% = 0.1

e = charge of electron 1.6×10^{-19} C

G = is the gain which is the amount of light detected and the energy of the cosmic muons.

Taking the mean value of the number of optical photons from the simulated data, we therefore have:

V = 0.16 from the experimental measurement as the mean value of the signal distribution of all the detectors as seen from figure fay.

R = 2m(ohms) from the simulation yield of the AnaBar detector

I = $\quad = 8 \times 10^{-8}$ A

Q = IT

At a constant time, response for all the detector measurement, t = 1ns and

I = 8×10^{-8} A,

Q = $1 \times 8 \times 10^{-8}$

Q = 80nC.

The EJ200 is the photomultiplier tubes (PMT) of the detector with quantum efficiency ($E_{quantum}$) of 10% which is equal to 0.1 from the manufacturer specification, while the charge of an electron is 1.6×10^{-19}C, so,

$Q = (N_{photons} * E_{quantum}) * e * G$

$G =$

$G_{PMT} = 5.3 \text{ X } 10^8$.

Using the value we measured from the $N_{photons}$ and energy deposited, we have the absolute gain for the PMT to be 5.3 X 10^8

For the time resolution of the detector, it is calculated from the given equation below:

$\sigma^2_t = \sigma^2_{scint} + \sigma^2_{PMT}$

where:

σ^2_t is the full width at half maximum of the pulse width of the selected detector at a given position within the active analyser. Which is taken from 15, σ^2_{scint} is the standard deviation which signifies the detector AnaBar time response and σ^2_{PMT} is the detector time resolution as a result of the above equation. We normalized the measurement of the standard deviation (RMS) because of variation in the simulation yield used in the initial measurement of the resistance as well as other variables from the simulation measurement from the AnaBar time response calculation.

So,

$\sigma^2_{PMT} = \sigma^2_t - \sigma^2_{scint}$

$\sigma_{PMT} = 4.86\text{ns}$

The time resolution for the PMT was calculated from the value of standard deviation as well as the $N_{photons}$ which mean the value of optical photons hitting the detector from the simulation data.

5.4 COMPARISON BETWEEN EXPERIMENTAL AND SIMULATION DATA

The experimental measurement with cosmic muons and the simulation data with cosmic, proton and neutron particles at a varying energy between 1 and 6 GeV, this enable us to compare the electromagnetic field effects with these particles from the detector geometry to the tracking efficiency, alignment and particle identification through hadronic calibration measurement and Monte Carlo simulation.

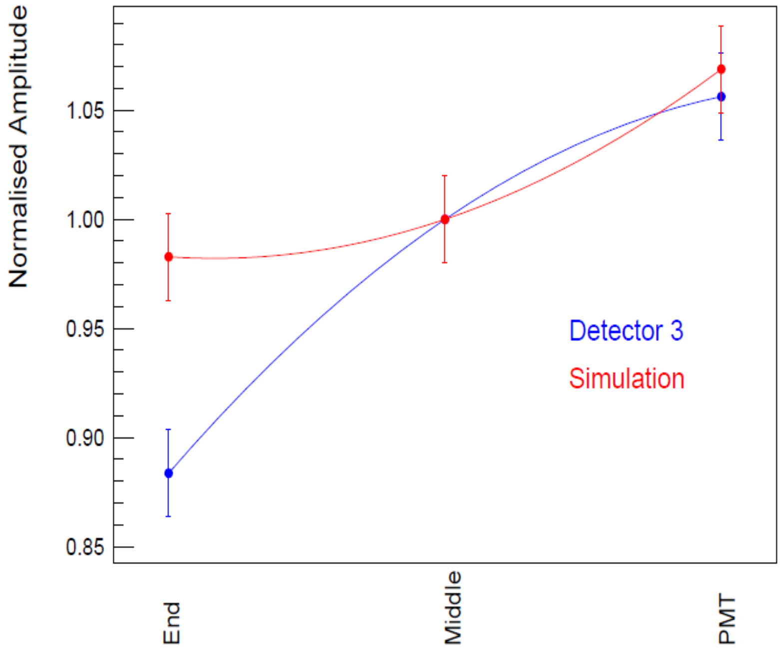

Figure 8: The Normalised signal for both experimental and simulation data as a function of position

In the figure 8 above, it illustrates how the experimental measurement with simulation data using cosmic muons varies at a different position of the detector, the normalized signal amplitude from figure 14, and the resistance from the simulation yield of the detector geometry for the neutron, proton and cosmic muon detection purposes.

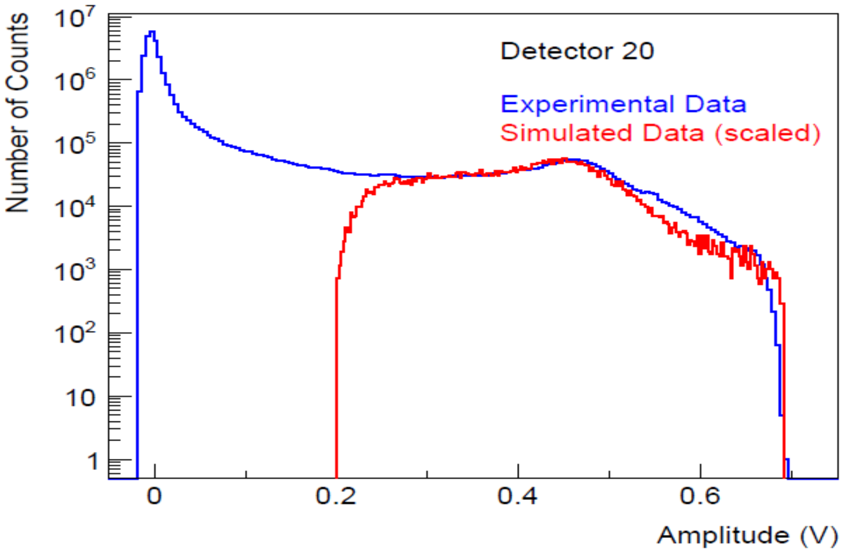

Figure 9: The comparison plot for experimental and simulation data as a function of signal amplitude

Figure 9 above illustrates the signal amplitude variation between the experimental and simulation data as a function of number of counts of the incoming photons. The experimental measurement shows the effects of noise in the signal generation due to optical grease loosing between the detector and the photomultiplier tubes as compared with the simulated measurement. Both results are within operational parameters of the incoming cosmic muons particle or proton and neutron.

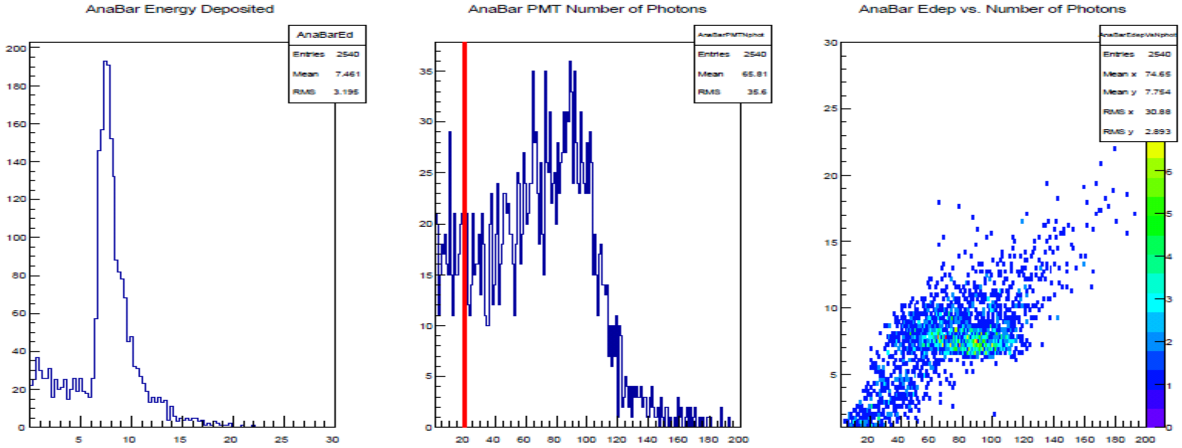

Figure 10: Simulation plot for cosmic muons as a function for both energies deposited and number of photons hitting the detector at efficiency of 0.8

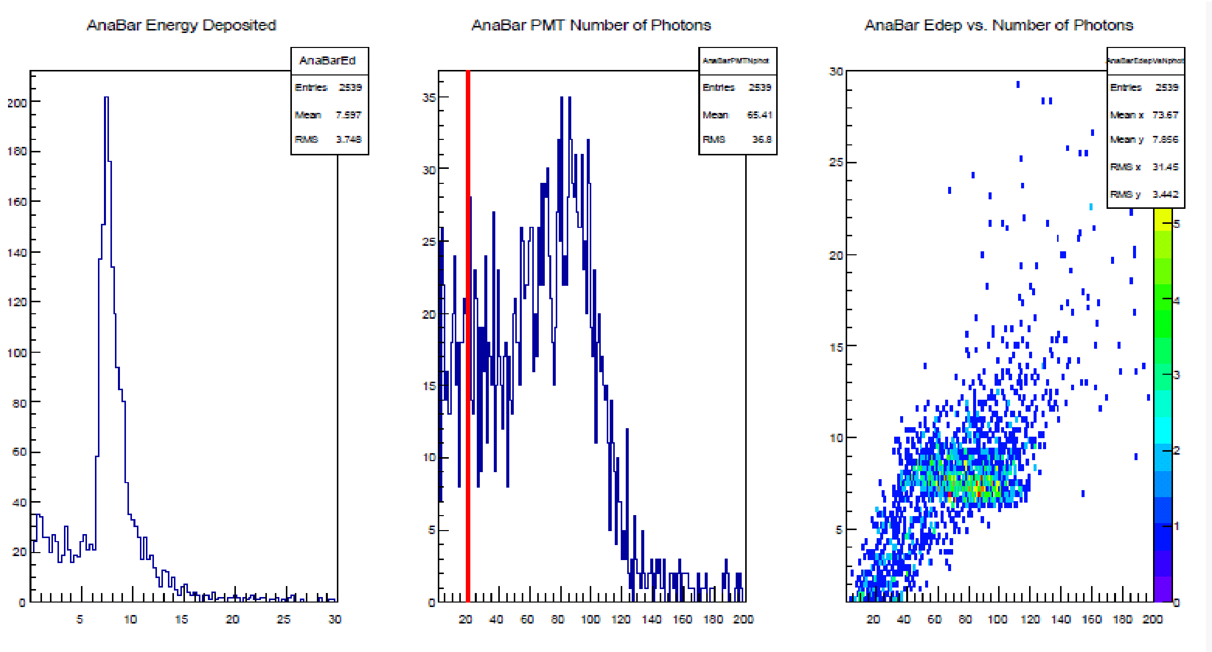

Figure 11: Simulation plot for proton as a function for both energies deposited and number of photons hitting the detector at efficiency of 0.8

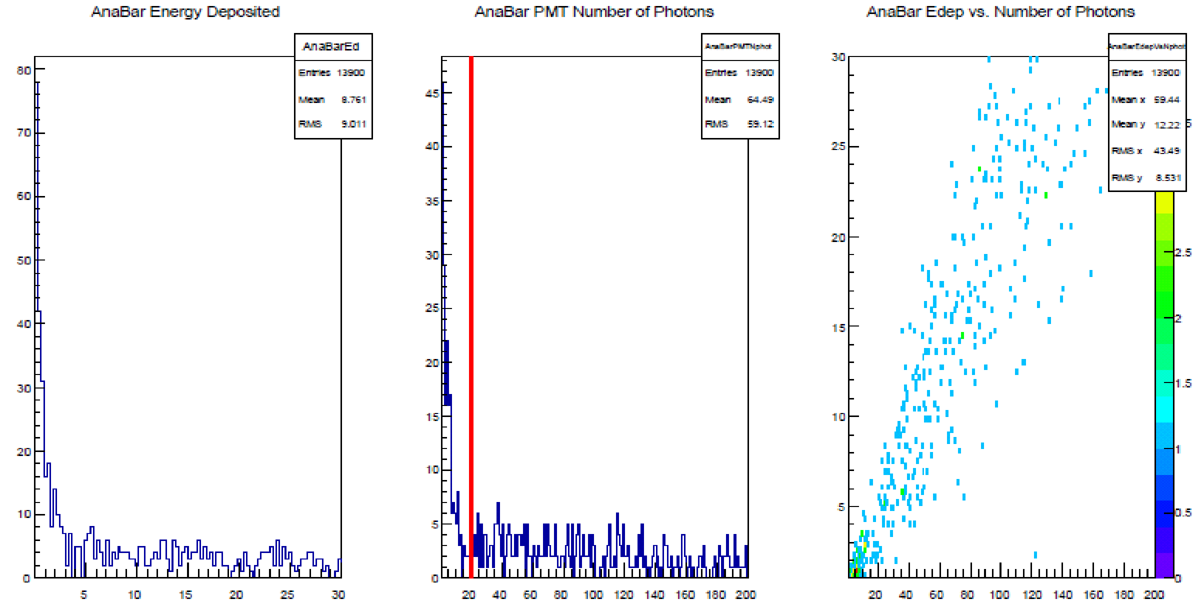

Figure 12: Simulation plot for neutron as a function for both energies deposited and number of photons hitting the detector at efficiency of 0.4

The active analyser is a component part of the hadron arm of the Super BigBite Spectrometer in the Jefferson Lab experimental Hall. It is designed to measure the recoil neutron polarimetry at the highest energy level ever. It consists of thirty-two detectors. The recoil neutron polarimetry at higher energy level will requires a good understanding of both detector and the physics of the background knowledge. This knowledge has been the driving force behind the work presented in this research work. This result showed a variation in the signal and noise amplitude, as the signal to noise ratio is high in some detector, with some detectors showing a low gain and others having relatively higher absolute gain as well as difference in the time resolution from the measured values. Also, the dependent of the signal amplitude against the various position of the active analyser with respect to the incoming cosmic muons showing a higher signal output close to the PMT as against the low signal at the far end of the active analyser.

The time resolution of the photomultiplier tube is within the operational parameter with the resolution of 5ns which means that the detector can take a ray of 200mHz. Also, the result from the lab and the simulation with cosmic muons look consistent and from the simulation result, the absolute gain of the PMT was extracted to be 5.3 X 10^8

Finally, the active analyser can now be used as a component part of the hadron arm of the Super BigBite Spectrometer at Jefferson lab having been fully commissioned as part of this research work, it can be put together with other component of the Super BigBite Spectrometer where it will be tested with cosmic muons.

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