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Characterization and Testing of SiPMs for a Next-Generation Neutron Detector

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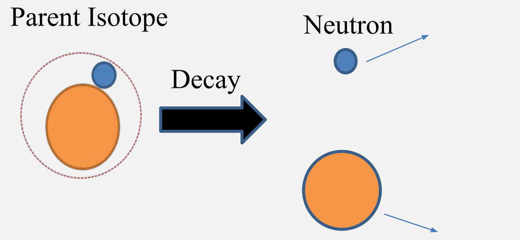
MoNA-LISA is a position-sensitive neutron detector at the Facility for Rare Isotope Beams (FRIB) used to probe neutron-unbound states through invariant-mass spectroscopy. Position resolution of the neutron detector is a key factor in invariant-mass measurements. A better neutron position would significantly improve the overall reconstructed decay energy resolution and would therefore lead to a better understanding of nuclei near and beyond the dripline. The MoNA collaboration is designing a next-generation neutron detector to improve the current MoNA-LISA resolution (~5cm). The new design will replace the PMTs for SiPM arrays as readout technology. The use of SiPMs (more compact) for neutron detection is being tested within the Collaboration and its performance characterized with a simple detector made up of a circuit board with SiPM sensors coupled to a plastic scintillator. The response of each SiPM has been studied. As position sensitivity is a main requirement for the planned next-generation neutron detector, a multitude of tests with cosmic rays and collimated gamma sources, such as ^{60}Co and ^{65}Zn, have been performed as well to evaluate the new design's position resolution. Along with these tests, algorithms have been developed to reconstruct the interaction point based on the light collected by the SiPMs.

Neutron Unbound Studies at FRIB

- The MoNA collaboration investigates neutron unbound systems near, at and beyond the neutron dripline. These systems decay immediately after being populated.
- The **invariant mass technique** is used to reconstruct the energies of the resonant neutron-unbound state. The invariant mass is the total relativistic energy of the system reconstructed from the measured 4-momenta of all decay products in any reference frame. The decay energy (E_{decay}) is defined as the difference between the invariant mass of the system and all the rest masses (m_i) of the decay products.

$$E_{decay} = M_{inv} - \sum m_i = \sqrt{\left(\sum_{i=1}^{N} E_i\right)^2 - \left(\sum_{i=1}^{N} p_i\right)^2} - \sum m_i$$



- This technique requires the detection of all decay products in coincidence. At FRIB, the current experimental setup for invariant mass spectroscopy measurements is the Sweeper-MoNA setup.
- The MoNA-LISA detector provides detection of the decay neutron and reconstruction of its momentum, which is key for the overall decay energy resolution.

Neutron Detection

- The **MoNA-LISA array** consists of 272 plastic scintillator bars with Photomultipliers Tubes (PMT) connected to either end of the bar. Neutron interactions within the bar induce the emission of visible light which travels to the PMTs (Fig. 1). The position of the neutron interaction is determined by the time difference between the two PMT signals.
- The MoNA Collaboration is looking to improve the current position resolution (~5cm) with the Next Generation Neutron Detector (NGND) by the use of Silicon Photomultipliers (SiPMs) as the readout technology in replacement of the PMTs. The NGND will consist of 128 tile modules with SiPMs laid out in a grid-like pattern (Figure 2). Based on simulations, it is expected that the new design will improve position resolution by at least 5 times.

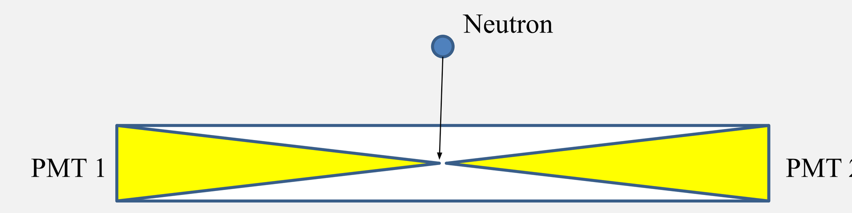


Figure 1: Current neutron detection using PMTs. Neutron impinged upon scintillating plastic (white), induces photon emission (yellow). The time difference between PMT signals is used to calculate the position of the neutron interaction

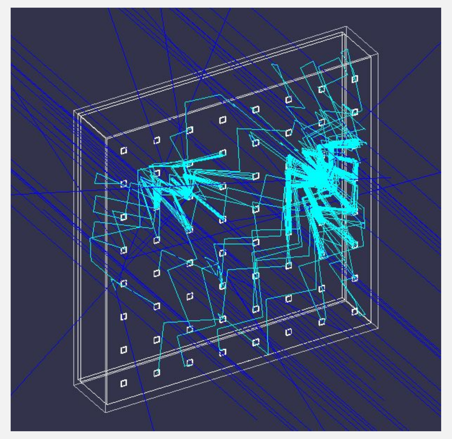


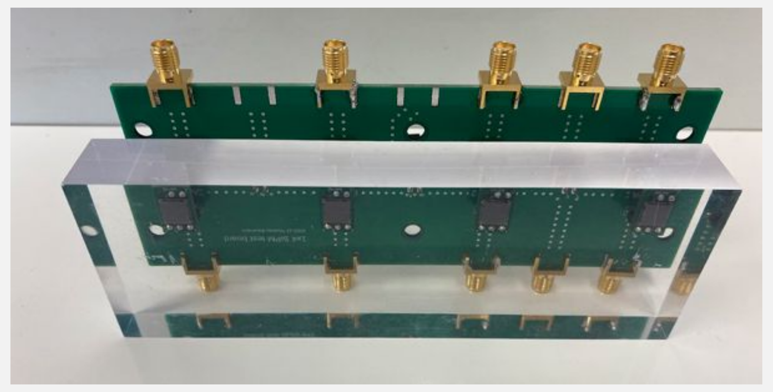
Figure 2: Simulation of neutrons interacting in a preliminary design of NGND. The emission of photons within the scintillator can be seen in light blue. Light is collected by the SiPMs (small squares). The greater the light output, the closer the interaction occurred to that SiPM

Characterization of SiPMs

The characterization of SiPMs for neutron detection has been tested with small scale test kits consisting of a circuit board, varying amounts of SiPMs at different positions and a plastic scintillator (Figure 3).

- The first tests studied the basic operation of the SiPMs, such as the **breakdown voltage:** minimum bias voltage required for the SiPM to be in Geiger Mode. Figure 4 shows how current increases with bias voltage, the breakdown voltage is found as the x-intercept of the fit. Values differ between SiPMs, which is important for gain matching. Light collected as a function of the overvoltage (difference between bias and breakdown voltage) was also studied to understand the **gain** (Fig. 5).
- As **cosmic rays** are needed for the high-energy calibration of the neutron detector, a number of tests with cosmic rays have been performed for different configurations of the boards (wrapped/unwrapped in Teflon tape, SiPMs optically coupled/uncoupled). See Fig. 6. Determining which configuration gives the best results (light collection, position resolution, etc.) is important for the design of the NGND
- A collimated **Pu-Be neutron source** was used as a low-energy neutron beam to study the response of SiPMs to neutrons, laying the groundwork for experiments at the Triangle Universities Nuclear Laboratory (TUNL) with higher energy and intensity neutron beams

Figure 3: Test Kit consisting of a green circuit board, four black SiPMs, clear scintillating plastic



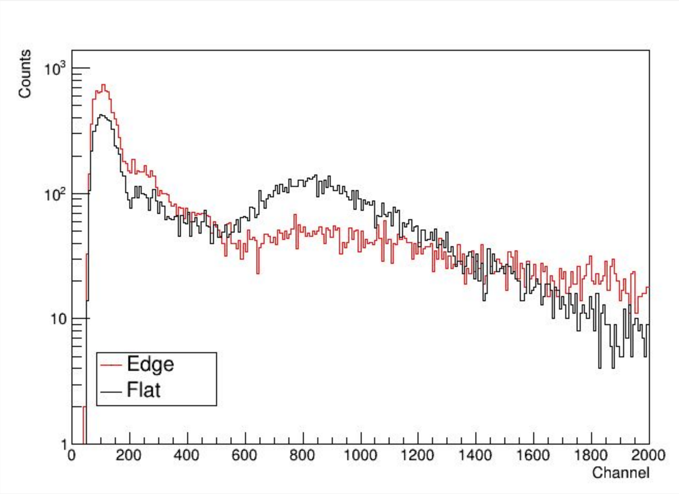


Figure 6: Cosmic ray spectrum for a wrapped and coupled configuration for both flat (black) and vertical (red) positions of the board

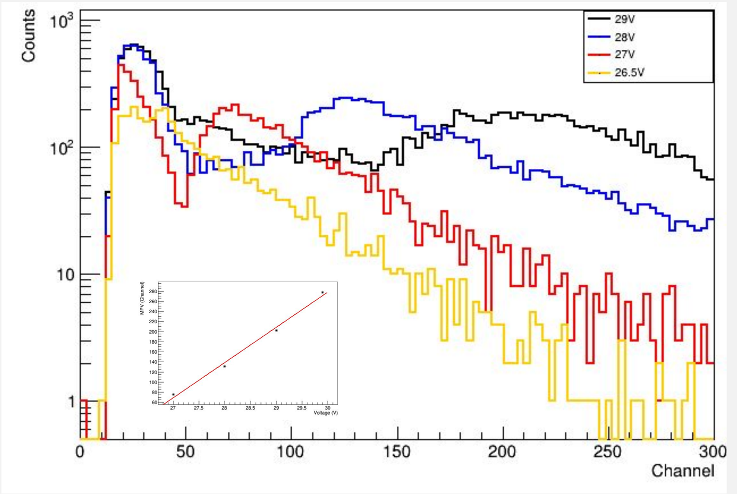


Figure 5: Evolution of the cosmic ray spectrum as a function of the bias voltage. As can be seen in the inset, the channel position of the cosmic ray peak increases linearly with the bias voltage

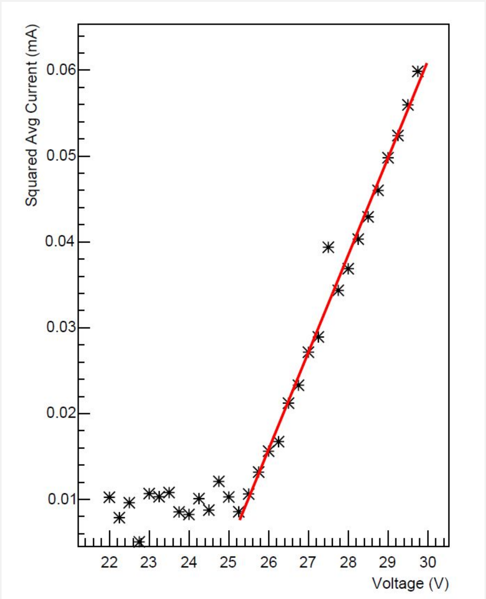


Figure 4: Breakdown voltage calculation, x-intercept of linear fit is the value of breakdown voltage

Algorithmic Determination of Position

The position sensitivity of the SiPMs is an important feature of the new detector design. Tests were performed using collimated gamma sources (^{60}Co and ^{65}Zn) with different testing configurations to determine what physical characteristics give the best output to determine position. These configurations included: the scintillator being wrapped in Teflon tape or not, optical coupling being present between the scintillator and SiPMs, differing bias voltages for the SiPMs and DAQ settings.

- The interaction position can only be calculated if information from multiple SiPMs is combined. Several algorithms were developed, among which the most successful is based on a **weighted average** using the amount of photons collected in each SiPM. The weighted average is the summation of each SiPMs light output multiplied by the position given to that SiPM, that summation is divided by the summation of all light outputs, in an event by event basis.
- Figure 7 is an example of the weighted average algorithm for four different positions of a collimated ^{65}Zn gamma source. The four positions are as follows: gamma rays directed between SiPM3 and SiPM4 (Green), between SiPM2 and SiPM3 (Black), at SiPM3 (Red), and at SiPM2 (Purple). The peak of the position distribution occurs near the position where the gamma beam was directed, proving that it is possible to determine position through these means.

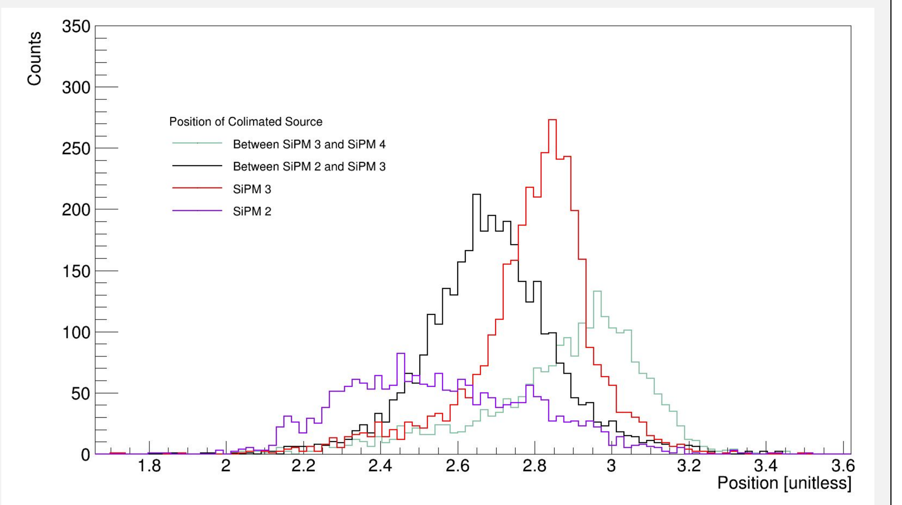


Figure 7: Weighted average results from four different trials where a collimated source was directed to different parts of the test kit. The configuration used was wrapped, coupled, and a bias of 29V

Future Steps

- In October of 2023, test boards were sent to the Triangle Universities Nuclear Laboratory (TUNL). At TUNL, an 11 MeV neutron beam impinged on the test boards in select locations. Analysis of this experiment is currently ongoing. Results will help benchmark simulations.
- Performance of machine learning algorithms to determine the position of a neutron interaction will be studied.
- Prototype tiles will be fabricated at Hope College. Tests with the prototype will extend the abilities of the weighted average algorithm into 2D rather than the current 1D resolution.
- Further tests will be conducted at TUNL or Los Alamos Nuclear Laboratory (LANL) for higher energy neutron beams (~200 MeV), similar to FRIB energies.

Acknowledgements

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