MoNA: the Modular Neutron Array

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Abstract

The Modular Neutron Array (MoNA), a large-area neutron detector, is being constructed to advance the study of rare, short-lived, neutron-rich nuclei. The array will be an arrangement of 144 individual detector modules, each consisting of a 200 x 10 x 10 cm$^3$ of BC-408 bar of plastic scintillator with photomultiplier tubes mounted on each end. The modules will be organized in a succession of nine vertical planes, which can be reconfigured for optimal performance. To increase detection efficiency for neutrons above 100 MeV, iron passive converters will be placed in front of the modules in the last six layers. MoNA is designed to measure the energy and position of the neutrons. The neutron energy is deduced from the time-of-flight relative to a start detector. The position is calculated from the time difference between the two photomultiplier tubes at each end.

Eight of the 144 detector modules composing MoNA were placed in a beam of intermediate energy neutrons produced from a 155 MeV/u $^{36}$Ar beam striking a 1 cm Al target at the National Superconducting Cyclotron Laboratory (NSCL). Micro-MoNA ($\mu$MoNA), the eight-module set-up, was arranged in two vertically stacked horizontal planes of four modules placed 5 m from the Al target. Two 1 cm plastic scintillator veto bars were placed in front of each horizontal plane. Tests were conducted with and without a solid brass shadow bar.
Introduction

The Modular Neutron Array (MoNA), a highly efficient large-area neutron array, will be constructed at the National Superconducting Cyclotron Laboratory (NSCL). First I will discuss the motivation for the construction of MoNA, the design details and the main functions of its components. Next I will present the assembly and testing details, location information, μMoNA and the MoNA Collaboration

Motivation

The motivation for constructing MoNA is the measurement of rare neutron-rich isotope properties. In order to study such nuclei, observations of what is produced after a reaction with them are needed. This is accomplished by colliding a rare isotope beam with a reaction target to yield reaction products. MoNA is specifically interested in the neutrons that are produced. Even more specifically measurements of neutron numbers, energy and momentum are of interest. The production of rare nuclear beams at the NSCL allows this study of such isotopes that are far from stability. Studying rare neutron-rich nuclei will give insight to their structure and interior. It will also provide answers to astrophysical questions, as neutron-rich isotopes are involved in stellar explosions and heavy element synthesis. In addition to providing a means to measure the properties of rare neutron-rich isotopes, the MoNA project serves as an immense educational tool for undergraduates.

Neutron Detection with MoNA

To make the measurements necessary to study the properties of rare neutron-rich nuclei, neutrons need to be produced. This is accomplished by the facilities at the NSCL. Neutrons are produced when a rare isotope beam collides with a target. However,
neutrons are not the only product of the collision. Many charged particles and gamma rays are also produced by the reaction. Since MoNA is particularly interested in the detection of neutrons, the collision products must be sorted. The sweeper magnet accomplishes the sorting of charged particles and neutrons. The sweeper magnet will be located in front of MoNA, as shown in Figure 1, a possible arrangement of MoNA.

Gamma rays will be detected in the germanium detectors. The quadrupole triplet is a magnet for focusing and defocusing the beam, it does not alter path of the beam. The neutrons will continue to MoNA and the charged particles will be swept to the charged particle detectors. This setup will make kinematically complete measurements possible and will allow for energy measurements of the fragments produced by the reaction.

![Figure 1 - Possible setup of MoNA with germanium detector array, sweeper magnet and charged particle detectors.](image)

**Design**

MoNA will consist of nine vertical layers of 16 modules, each layer having a frontal surface area of 200 x 160 cm². The individual modules allow for reconfiguration of MoNA to optimize performance. Depending on the type of rare isotope beam and reaction target used, the cone of products may have different shapes, or only a specific
section of the cone may be interesting. MoNA can be reconfigured to best fit the area of interest.

![A rendering of assembled MoNA.](image)

**Figure 2 - A rendering of assembled MoNA.**

Each module is made from a Bicron BC-408 organic plastic scintillator bar with light guides on either end. The bars are manufactured at Bicron with light guides and flanges for mounting two inch Photonis XP2262/B photomultiplier tubes (PMTs). Each bar is wrapped in aluminized mylar to trap light that exits the bar. The bar is coated with black plastic and tape to ensure that no external light enters the scintillator material. Since magnetic fields can affect PMTs, a mu-metal shield will surround each PMT as a magnetic shield. MoNA is designed for neutrons with energies 50 MeV to 250 MeV [2].

**Module Operation**

Neutrons cannot be directly detected, but their reaction with protons can be. When a neutron collides with a proton in the scintillator bar, the proton recoils and interacts with an atom in the plastic, exciting it, and light is released when the atom de-excites as shown in Figure 3.
Figure 3 – Neutron interaction with the scintillator. \( p \) is the proton that recoils after the neutron interacts with it. \( n' \) is the neutron's path after the interaction in the scintillator. The green line indicates the path the light signal takes.

The light travels down the bar to the PMTs, where it is converted into a usable signal. By using the signal timing differences from each end of the bar, the position of the neutron can be determined. The expected position resolution for MoNA in the horizontal direction is 7 cm FWHM.

**Passive Converters**

Iron sheets will be placed between the last six layers of scintillator, to serve as passive converters. When neutrons hit the iron, which is more densely packed than the plastic scintillator, more interactions occur. The charged particles resulting from those interactions are then detected in the next layer of scintillator. It is not possible at first sight to determine if the charged particles detected after the iron sheets are from actual interactions of neutrons with the iron or if they are random charged particles. This can be determined by tracing the paths of the neutron in the front layers. The first three layers will not have iron sheets between them to detect the lower energy neutrons without stopping them in the iron. The passive converters will increase MoNAs detection efficiency for neutrons above 100 MeV. As shown in Figure 4, with passive converters, MoNA will have a detection efficiency of 70%, which means it will detect 70% of all neutrons that enter the detector [2]. MoNA will be significantly more efficient than the existing neutron walls at the NSCL. Passive converters make it possible to have a higher efficiency with fewer layers of scintillator.
Figure 4 -

The simulated detection efficiency vs.

neutron energy is shown on the right, with (red) and

without passive converter (green). The black line

indicates efficiency of existing neutron walls.

Assembly

Two of MoNA’s 16 layers were assembled and tested by undergraduate students at the NSCL. Assembly of an individual module requires that a PMT is surrounded by a mu-metal shield and is mounted to the light guide on each end of the bar. To prepare for mounting, each PMT is wrapped in black electrical tape to insulate it from the shield. An o-ring is placed on the PMT to hold the PMT in the center of the mu-metal shield. A Photonis VD122KB voltage divider base is connected to each PMT. The tubes are fused with black silicon caulk to the mu-metal shield. Optical coupling grease is applied to the light guide in order to couple the scintillator and the PMT. The coupling grease and the scintillator have similar indices of refraction. The mu-metal shield and PMT combination is mounted to the flange at the end of each bar. A ring of black felt is used between the flange on the bar and the mu-metal shield. The felt compresses as the shield is screwed on and keeps light from entering at the connection [2].
**Testing**

Each of the 144 modules will be individually tested. Testing is necessary to determine each scintillator bar’s attenuation length and time-position relationship. Any imperfections in the scintillator or defective connections between the PMT and the light guide are noticeable in the test results, therefore testing each individual bar is important.

Each bar is first tested for light tightness. Since neutron events are given by a light signal reaching the PMT, it is important that no outside light enters the bar and taints the detection signal. Testing for light tightness is done by applying a voltage around 1500 V to both PMTs on a bar and using an oscilloscope to view the signal. Once the voltage is applied the areas of the bar where possible light leaks could occur are covered with a dark material. The material is removed and if the signal does not change in shape or intensity, the module is deemed light tight. If the signal shows a sudden increase in intensity when the material is removed, a light leak is found and fixed with black electrical tape. Once light tightness is assured, gain matching of each PMT is completed.

*Figure 5 - Rendering of module assembly*
Testing to determine the attenuation length of each bar is then completed. The attenuation length is the length by which the signal’s light intensity is reduced by a factor $1/e$ [1]. This is found by correlating the peak channel of spectra taken with a gamma source at specific positions along the bar, as shown in Figure 6.

**Figure 6** - *Spectra taken for bar attenuation length testing with a Bismuth-207 source.*

*The blue curve is produced when the source is 80 cm from one end of the bar and the red curve is produced when the source is 140 cm from the end of the bar. The shift in the peaks is due to attenuation.*
Figure 7 - Spectrum produced for time-position testing with a Bismuth-207 source 25 cm from one end of the bar.

Module time-position relationships are also examined. This is completed by placing a gamma source at various positions along the bar and recording the peak channel of the spectrum produced, as shown in Figure 7. The peak channel and position relationship should be linear, to ensure that light travels the same way in every part of the bar.

Two layers of MoNA, 32 individual detectors, have been assembled and tested at the NSCL by undergraduate students (Melanie Evanger, Mustafa Rajabali, Ramsey Turner).

Testing Electronics

The electronics used for testing each individual module involve multi-channel analyzers (MCAs), constant fraction discriminators (CFDs) and time-to-amplitude converters (TACs).
Figure 8 – Simple electronics setup for bar attenuation length testing.

Figure 9 – Simple electronics overview for measuring signal timing differences in PMTs.

Location

MoNA will be located in the high bay area of the NSCL. This will allow it to be used concurrently with other detectors, such as those used to detect charged particles and gamma rays.

Figure 10 - Location of MoNA
Testing with intermediate neutrons produced from an $^{36}$Ar 155 MeV/u beam striking an Al target was completed with an eight bar subset of MoNA, µMoNA, at the NSCL. The bars were arranged in two horizontal planes of four detectors as shown in Figure 11. In front of each layer was a veto paddle, composed of a 112 x 1 x 10 cm$^3$ scintillator bar. The veto paddles were used to tag charged particles entering the MoNA bars so that neutron events could be distinguished. The electronics setup for the neutron detection test involves similar components as electronics setup for individual bar testing, however it is much more complex. For a complete electronics overview, refer to [http://groups.nscl.msu.edu/mona/microMoNA_electronics.pdf](http://groups.nscl.msu.edu/mona/microMoNA_electronics.pdf). The difference between the electronics setup for individual bar testing and neutron detection tests is the use of triggers. Triggers are used for the neutron detection tests requiring a signal from the start detector and a signal from a bar to happen within 250 ns of each other. When this it true, the computer is told that the event is possibly a good event and all the information is then recorded.

**Figure 11 - µMoNA setup for neutron detection.**
The Al reaction target was placed 5 m from the detectors. Beam runs were completed with and without a 27.40 x 5.10 x 7.65 cm$^3$ shadow bar 241 cm (measuring from the back of the bar, downstream from the beam) from the detectors modules. The shadow bar tests will be used to determine the horizontal position resolution of MoNA. The shadow bar was placed in the bottom horizontal plane, in the center of the bars. The shadow of the shadow bar on the bottom modules is what is interesting. The shadow bar was located halfway between the reaction target and the modules. Figures 12 and 13 show the x-position spectra produced for the first bars in the shadow bar run. The x-position is the position along the bar where the neutron entered. The data is read in by the electronics and placed in bins or channels. There is a correlation between the channels and the number of centimeters along the bar. In Figure 12 the shadow bar is not in the production cone’s path, whereas in Figure 13 the position of the shadow bar along the bar makes a visible shadow. The black curves in both Figure 12 and Figure 13 are from raw data. By analyzing the data from the shadow bar run the horizontal position resolution of the MoNA modules can be determined. The neutron energy is deduced from the time-of-flight relative to a start detector located 24 cm before the reaction target. The data for the neutron detection test is currently being analyzed. It will present the first neutron energy spectrum measured with $\mu$MoNA as well as the position resolution of the detectors.
Figure 12 - Graphs show the x-position of bar three, the first bar in the top layer of the μMoNA setup, where the shadow bar is not in the production cone. The black curve shows x-position when the veto is not applied, the blue shows x-position when NOT-gated with veto.
Figure 13 - Graph shows the x-position of bar seven, the first bar in the bottom layer of the \( \mu \text{MoNA} \) setup, where the shadow bar is in the production cone. The black curve shows x-position when the veto is not applied, the blue shows x-position when NOT-gated with veto.

The MoNA Collaboration

The MoNA Collaboration consists of a consortium of ten undergraduate institutions that are constructing MoNA. The collaborators involved are Ball State University, Central Michigan University, Concordia College, Florida State University, Hope College, Indian University South Bend, Michigan State University, Milikan University, Western Michigan University, and Westmont College. Each of the nine layers of MoNA will be constructed and tested by undergraduates, under the direction of their professors, at one of the involved institutions. The students will assemble and test
each of the detector modules and they will also have the opportunity to partake in the complete assembly of MoNA.

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