Calibration of the Modular Neutron Array (MoNA)

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In recent years the study of exotic nuclei has become of more interest to the nuclear physics community. By studying extreme nuclear structures we can come to a greater understanding of the patterns and forces involved in the creation of stable nuclei. Many of these more exotic nuclei are very short lived and it is difficult to study them as a result. At the National Superconducting Cyclotron Laboratory it is possible to create these exotic nuclei and to move them at great velocities, in the neighborhood of one half of the speed of light. Moving at these velocities allows us to study these exotic nuclei before their rapid decay into a more stable isotope. Using a procedure of nuclear breakup it is possible to work backwards and extrapolate the makeup of the parent nuclei. The exotic nuclei that have been of particular interest lately are those that are close to the “neutron drip line” – called this because of the extreme proportion of neutrons and that
some become neutron unbound. When these neutron heavy nuclei are broken apart the most common resultant products are neutrons. In order to study these nuclear neutron reactions a new high-efficiency neutron detector has been designed and fabricated by a collaboration of ten colleges and universities. The Modular Neutron Array (MoNA) can detect up to 70% of the neutron events that occur within it.

\[ \text{Figure 2 - Efficiency of MoNA compared to old methods. The black line represents the efficiency of the old neutron walls. The dots represent MoNA’s expected efficiency. Closed dots for MoNA with passive iron converters. Open dots for just MoNA bars.} \]

High precision measuring devices, such as MoNA, require a high level of accuracy when attempting to carry out their measurements and so a very precise and thorough method of calibrating is required. This paper will look at three very important features of MoNA that must be calibrated correctly in order to ensure that it is functioning at the optimal level.

**Structure of MoNA:**
As the name implies, MoNA is a modular detector. It is made up of 144 identical bars. A single MoNA bar is comprised of several features, which work to create an overall highly efficient design. Each bar is made of a plastic scintillating material covered with a reflective material, to prevent light contamination to other bars, and is encased in a black casing. Each end of the bar is capped with light guides and a photomultiplier tube (PMT). The concept is that a neutron will hit the bar and cause a flash of light in the plastic, which will then be transmitted to the PMT and be amplified and sent on to the electronics for processing. This amplified signal is then sent to a constant fraction discriminator (CFD) to transform the linear pulse of the PMT into a logic signal that the rest of the electronics and the computers can understand. After passing the CFD, the signal is then passed through a time-to-digital converter (TDC) and a parallel signal is sent from the PMT to a charge-to-digital converter (QDC).
This design then creates the need for the three calibrations previously mentioned. A PMT is not guaranteed to be exactly identical to any other PMT and as such will send out signals at different amplitudes. In order to compensate for this difference the driving voltage around the PMT tube needs to be adjusted until the tubes produce signals at equivalent amplitudes. The second calibration that needs to be performed is the calibration of the TDCs. Individual characteristics of the TDCs prevent them from giving identical signals as well. The final calibration that needs to be performed is really a scaling operation that can be performed in the software and is not actually a concern for the hardware of MoNA. The signals from the properly calibrated TDCs are used to create spectra identifying the positions of the various detected events in the MoNA bar. These position spectra must be properly scaled to give a proper width and center to the data.

**Gain Matching**

As mentioned above, each PMT is unique. Differences in the manufacture and impurities in the raw material lead to different response characteristics. When an event occurs within a MoNA bar a light flash is given off and travels down the bar to either end and is picked up by the PMT. Events that have lower energies may be detected by one PMT on a bar but not the other due to the sensitivity differences. In order to compensate for these differences the voltage on the weaker tube needs to be raised so as to detect signals better. A routine has been established for doing this that greatly reduces the tedium that would be sure to result from hand tuning all 144 bars (or 288 PMTs!) to the necessary voltages.
Calibration of the MoNA bars is simple in theory and relatively easy to comprehend in practice as well. The only known reference that we can calibrate to is the expected background radiation. So, in order to do this all 288 PMTs are activated and scaled up to their appropriate voltages. They are then left to run and record data without any radiation source or cyclotron beam activity. After enough time has elapsed to allow for sufficient statistics to be recorded we have all the data we need to perform the calibration.

Figure 4 - A picture of a MoNA QDC spectrum. Note the cosmic peak near 20 MeV, this shows a properly Gain Matched tube.
A two component fit – consisting of a Gaussian and an exponential – are then applied to each of the spectra in order to verify the location of a cosmic ray peak in the spectrum. Generally speaking muon type cosmic rays leave an estimated 22 MeV in the bars and it should be verified that this peak is properly placed. By changing the voltages on the PMTs we can shift the location of the cosmic ray peak. This can be done through several iterations until the location of the peak is correct. The automated process for doing this (written by MoNA group member Ken-ichiro Yoneda) can quite obviously save an experimenter much time.

**Time Calibration:**

The time-to-digital converters (TDC) give us information on the time of flight of a neutron (from the sweeper’s detector to MoNA) event. When a particle strikes a detector in the sweeper magnet prior to entering MoNA, this creates a start on the timing circuit. The TDC then begins to charge a capacitor and once the particle (or fragment of the particle) strikes MoNA a stop signal is given (Strictly speaking this is not an entirely accurate statement. We actually have enough of a delay set into the sweeper electronics so that the start signal actually comes from MoNA and the stop then comes from the sweeper.). By reading the level of charge stored in the TDC’s capacitor it is possible to know fairly precisely how long it took the particle to fly from the sweeper to MoNA. However, due to the unique properties of each individual TDC and capacitor it is quite common for there to be discrepancies in timings that should be identical events. In order to correct for this it is necessary to calibrate the TDC capacitors to a standard charge and discharge rate. This is done using a device that is appropriately called a Time Calibrator.
The Time Calibrator works by sending out an electronic pulse at very specific, very regular time intervals. The beginning of the pulse acts as a start and the end of a pulse as a stop. This signal is then fed through all of the TDCs and a time spectrum is generated. Since we know that the Time Calibrator is giving a regular, consistent pulse we can then form a relationship between the released pulse and the recorded data. Using this relationship we can then instruct the software to correct for the individual differences in the TDC characteristics. The TDC spectra can then provide us with an accurate description of the times-of-flight of the particles and (eventually) the position of the particle’s impact within the bar.

Position Calibration:
Figure 5 - A picture of an X position spectrum for a MoNA bar. Note that the edges are right at -100 and 100. The extra counts outside the length of the bar represent an artifact created by the ends of the bars.

Once the TDCs are properly calibrated to give accurate data we are then ready to calibrate the position spectra of the MoNA bars. A MoNA bar is 200 cm long with a 10 cm by 10 cm cross sectional area. By calculating the difference in timing between one side of the bar and the other we can get a fairly reasonable idea of where in the bar the particle hit. However, the biggest possible difference in times in a MoNA bar is 25 ns, which does not give a very detailed picture of the position of the event within the bar.

We wish to know the position of the particle to within a few centimeters and so we need to perform some scaling operations on the time difference spectrum.
To scale the raw time difference spectrum to a calibrated position spectrum is a relatively simple procedure. Again a run of cosmic rays needs to be taken, allowing enough time for sufficient statistics to develop. First we must briefly look at the theory behind the cosmic and background radiation. Cosmic rays enter the atmosphere in pretty much all angles, except those directly blocked by the earth itself. So, when attempting to calibrate the position spectrum of a bar (along the 200 cm direction) one would expect the position spectrum to have a uniform distribution of cosmic background, with no preference for any particular position. In order to calibrate the position spectrum we need to scale the 25ns wide time difference spectrum to a 200 cm wide spectrum that is centered around zero. Thankfully, a computer program has been written (by Jean-Luc Lecouey, another MoNA group member) that will do this automatically for all 144 bars of MoNA.

Final Remarks
Figure 6 - A display of the counts in each of MoNA's 288 PMTs. This is from a run only with cosmic rays...no beam.
Figure 7 - This is a display of all the counts in the MoNA PMTs with the cyclotron beam on. The level of the beam can be clearly seen in the varying counts clustered around the front and middle layers of MoNA.

As the two figures above clearly demonstrate we have made a successful test run of MoNA with a cyclotron beam on. Each PMT was gain matched so that the signal amplitudes sent out were standardized. Due to the threshold values (the minimum acceptable signal amplitudes) we know that the two figures above are accurate.
representations of the rate of events in the PMTs. Without the gain matching we would not have been able to say that with 100% certainty. The plots below show how the beam is hitting the middle bars and how there is peaking, which is an indication of incident neutrons.

Figure 8 - Bars no. 6,7,8,9,10 of layer A (the layer the beam strikes first). Notice how in the middle 3 bars there is a noticeable peak. This is an indication of neutron-fragment coincidence with MoNA and the Sweeper Magnet.

Perhaps the most important thing to come out of this project is the extensive involvement of undergraduate students, both in the fabrication and running of MoNA.
Nearly all of the schools participating in the collaboration are predominantly undergraduate and had students actually build the MoNA bars. Some schools have even sent students to the NSCL to help with the final details and the commissioning experiment. The calibration procedural manual, which this paper refers to extensively, was actually authored by several students of the MoNA collaboration.

With this calibration successfully in place MoNA is ready to track neutrons and explore the breakup reactions of many of the exotic nuclei near the neutron dripline. It is believed that MoNA will be able to explore these exotic nuclei all the way up the chart of the nuclides up to $^{50}\text{S}$. 

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