Tracking Single and Multiple Neutron Events in the Modular Neutron Array (MoNA)

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Abstract:
The Modular Neutron Array MoNA is a large area detector consisting of 144 plastic scintillating bars housed at the National Superconducting Cyclotron Laboratory (NSCL). Used in conjunction with a 4 T sweeper magnet, it is a high-efficiency neutron detector for studying nuclei near or past the neutron drip line. First experiments concentrated on the study of nuclei decaying by single neutron emission. However, future experiments are planned to explore for example the decay of $^{13}$Li into $^{11}$Li and two neutrons. Thus it will be necessary to distinguish one-neutron hits from two-neutron hits in MoNA.
We attempted used the data from the decay of $^{25}$O into $^{24}$O and a neutron as well as the decay of excited $^{11}$Be into $^{10}$Be and a neutron to characterize single neutron events.

1. Some Context
   A. **Data Analysis**
      For the bulk of the analysis, I used Ron Fox’s SpecTcl, with Dr. Daniel Bazin’s TreeParameter mod pack attached. SpecTcl is a multi-faceted nuclear event data analysis program that allows quantification of data via histograms and 2D intensity plots.

      In large part, SpecTcl derives its power from its use of Tcl (Tool Command Language; pronounced ‘tickle’) a scripting language that allows the user to modify and perform operations on variables at the command line and (to some extent), write object-oriented scripts to analyze data.

      SpecTcl calls any type of plot a spectrum, so when I mention spectra, I am referring to a SpecTcl plot, rather than data I’ve taken from SpecTcl to analyze in another data utility.

   B. **SpecTcl Analysis**
      SpecTcl allows the user to define several types of gates:
      
      i. Geographic gates, such as a slice (a section of a histogram) or a contour gate (a section of a two dimensional intensity plot).
      
      ii. Logic gates, such as ‘and’ gates, ‘or’ gates, and ‘not’ gates.

2. MoNA Basics
   The detection of neutrons is a delicate process; since neutrons are not charged particles, one has to be very clever and find a way to use neutrons to produce either photons or charged particles, which are directly detectable. One solution is to use a plastic scintillating bar, as shown in figure 1.

![Fig 1. A Plastic Scintillating Bar with PMTs attached. [Marley, 2003]](image-url)
A neutron is incident on a detector bar. If it reacts, we may see the situation modeled in figure 1; a neutron incident on a molecule in the scintillating bar (typically $^{12}$C or $^{1}$H) scatters off of the molecule and, in the collision, dislodges a proton from the target molecule.

Photons produced in the collision will travel down the scintillating bar to a photomultiplier tube (PMT) at either end. The photomultiplier tubes convert incident photons with wavelengths in the ultra-violet to near infrared region to electronic signal. MoNA’s photomultiplier tubes have five parts (as shown in figure 2). The detection process is as follows:

i. The photocathode: photons incident on the photo-cathode (the small wave vector in fig. 2) cause it to expel one or more electrons.

ii. The electron (or electrons) are focused and accelerated by the focusing electrode towards the first dynode in the dynode array, resulting in the release of more electrons.

iii. A greatly magnified pulse, (on the order of $10^7$) electrons, eventually reaches the anode, which outputs data on electron characteristics to MoNA’s onboard computer for later analysis.

MoNA is, as its name suggests, a modular detector. At the time of writing, it was in a 9 by 16 configuration, and we divide it into 9 layers, labeled A to I, and 16 bars, numbered 0 through 15. In figure 3, the highest bar in MoNA’s facing side is A15, while the lowest is A0.

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1 The incidence in figure 1 is not a head on collision; if it were, the neutron would lose all of its energy and the result of the collision would be a dislodged proton with nearly all of the neutron’s energy.
3. Time Calibrating MoNA

MoNA is a fairly complicated detector. The scintillating bars are made to be as uniform as possible, but it is of course impossible to ensure that they all are entirely similar. Thus, it is necessary to calibrate each bar in MoNA in order to suppress undesirable characteristics. We developed the method for and performed the first such calibrations this summer.

Cosmic rays are a natural choice for timing calibration; MoNA detects them very easily, providing us with sufficient amount of data for our results to be statistically significant. More importantly perhaps, cosmic rays have been studied extensively for over 50 years, so we know enough about them to use them as a yardstick.

A cosmic ray moves through MoNA at approximately 29.87 cm/ns. Since a bar is 10.26 cm square, a cosmic ray on a straight trajectory should travel through MoNA at ~0.34 ns/bar, so if we were to subtract the average time of a straight cosmic hit in A7 from the average time of such a hit in A8, we should see a difference of 0.34 ns. Likewise, for A8 – A9, we should see a difference of 0.68 ns.

To calibrate these offsets, we arbitrarily choose one bar to be our gold standard (we chose A8) and find the difference in average time between hits in it and hits in every other bar in that layer. Next, we find the average distance between B0 and every other bar in the B layer, and so on until we have time differences for all 9 layers. Then we find the average distance in time between A15 and B0, and so on for the remaining 7 layers.

After recording average time differences for all 144 bars, we calculate what these values should be based on the geometry of MoNA and the velocity of a cosmic ray (Table I). The value in the column on the far right will be inserted into a timing offset file for SpecTcl to refer to during analysis.

<table>
<thead>
<tr>
<th>Path</th>
<th>Measured</th>
<th>Calculated</th>
<th>Difference</th>
<th>Adjusted wrt A8</th>
</tr>
</thead>
<tbody>
<tr>
<td>A15-B0</td>
<td>-4.87</td>
<td>-5.17</td>
<td>-0.30</td>
<td>-0.10</td>
</tr>
<tr>
<td>A15-C0</td>
<td>-3.97</td>
<td>-5.21</td>
<td>-1.24</td>
<td>-1.04</td>
</tr>
<tr>
<td>A15-D0</td>
<td>-3.33</td>
<td>-5.27</td>
<td>-1.94</td>
<td>-1.74</td>
</tr>
<tr>
<td>A15-E0</td>
<td>-2.45</td>
<td>-5.35</td>
<td>-2.90</td>
<td>-2.70</td>
</tr>
<tr>
<td>A15-F0</td>
<td>-1.97</td>
<td>-5.45</td>
<td>-3.48</td>
<td>-3.28</td>
</tr>
<tr>
<td>A15-G0</td>
<td>-1.79</td>
<td>-5.56</td>
<td>-3.77</td>
<td>-3.57</td>
</tr>
<tr>
<td>A15-H0</td>
<td>-2.27</td>
<td>-5.70</td>
<td>-3.43</td>
<td>-3.23</td>
</tr>
<tr>
<td>A15-I0</td>
<td>0.03</td>
<td>-5.85</td>
<td>-5.88</td>
<td>-5.68</td>
</tr>
</tbody>
</table>

Table 1: Diagonal Timing Offsets from Ex. 05039, Breakup of 25O. Values are in ns

2 William Peters, private communication [2005].
3 A15-B0 models a cosmic moving down and slightly diagonal; it is calculated to have a flight time of 5.17 ns, as opposed to a flight time of 5.10 ns for a cosmic straight down from A15 to A0.
4 The time offset from A8 to A15 for 05039 was 0.20 ns; that value was added to each diagonal difference for the final offset.
Due to unavoidable variations in the voltage settings of the PMTs over different runs, this calibration must be performed each time the voltages are changed. This is time consuming, since the positions of 144 average time difference peaks must be taken. However, we have automated the creation of the required difference spectra for this calibration, so it would be relatively simple to write a program to take the peak positions, saving a fair amount of time.

4. Data Analysis Basics

Each event in MoNA is composed of up to 20 hits. A standardized set of measurements are taken for each interaction:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>SpecTcl Label</th>
<th>Eff. Range</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of Flight</td>
<td>TOF_hit_n</td>
<td>-50 to 350</td>
<td>ns</td>
</tr>
<tr>
<td>X position</td>
<td>X_hit_n</td>
<td>-150 to 150</td>
<td>cm</td>
</tr>
<tr>
<td>Y bar</td>
<td>Y_hit_n</td>
<td>0 - 15</td>
<td>bar</td>
</tr>
<tr>
<td>Z</td>
<td>Z_hit_n</td>
<td>1 - 9</td>
<td>Layer</td>
</tr>
<tr>
<td>Kinetic Energy</td>
<td>KE_hit_n</td>
<td>0 - 200</td>
<td>MeV</td>
</tr>
<tr>
<td>Deposited Charge</td>
<td>Q_hit_n</td>
<td>0 - 150</td>
<td>MeV</td>
</tr>
<tr>
<td>Angle between X,Y</td>
<td>Theta_hit_n</td>
<td></td>
<td>deg</td>
</tr>
<tr>
<td>Angle between X,Z</td>
<td>Phi_hit_n</td>
<td></td>
<td>deg</td>
</tr>
<tr>
<td>Multiplicity</td>
<td>Multi_hit</td>
<td>0 - 144</td>
<td></td>
</tr>
</tbody>
</table>

These events are ordered 1 through 20 in the order they are recorded by the detector’s electronics. However, it is possible that the time of flight in TOF_hit_1 is not the shortest time of flight, so in order to find the first neutron interaction in an event, we must first find the first hit in time for the event.

It is also possible that there are less than twenty hits in an event. MoNA defines a valid hit as an interaction that causes the left and right PMTs of a given scintillating tube to fire within a set period. MoNA uses the difference of time from the firing of one PMT of a scintillating bar and the time of firing of the opposite to determine where in the bar the hit happened (since the speed of light is a constant, and the PMT detects photons, this is not only reasonable; it’s brilliant). MoNA calls this the X position of the hit, and assigns this value to X_hit_n. Knowing which tube’s PMTs fired, and where the interacting bar is in the 9 by 16 scintillating grid immediately gives MoNA the

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5 There is some doubt if variations in voltages significantly affect timing; variations are normally on the order of less than 50 picoseconds. However, it was felt that until we knew for certain, the safe thing would be to continue to calibrate.
Z (depth) and Y (height) of the hit. These values are then assigned to Z\_hit\_n and Y\_hit\_n, so if we know X, we get Y and Z for free. MoNA keeps on tracking the event for up to 20 hits.

If, on the first hit of an event, only one PMT on a scintillator fires, then the event is considered to be invalid: MoNA assigns multiplicity 0 to the event, and no data is taken. If a PMT pair fails to fire in harmony after the first hit, but before the 20\(^{th}\) hit, the event ends with the previous hit, and the number of valid hits (pair PMT firings) becomes the multiplicity of the event.

5. Time Ordering Hits

Our goal is to be able to differentiate between events composed of one neutron interacting multiple times and multiple neutrons interacting once (or more than once; if we can identify the difference between 1 neutron events and n neutron events, the number of interactions should be trivial). In order to characterize an event, we must identify the first interaction in the event; we want to know what kind of collisions happened, so we can predict an energy range for other hits in the event. Once we have this information, we can compare the recorded energies to the predicted energies and identify which hits were proton interactions and which were neutrons.

As I mentioned in the previous section, reactions in an event are recorded in the order they are ‘seen’ by MoNA, which is not necessarily the order in which they actually happen. Thus, in order to find the first reaction in an event, we first had to time order that event’s TOF hit spectra.

SpecTcl uses Tcl to allow the user to write object oriented scripts, so time ordering was fairly simple; I wrote a function to sort the TOF values of the valid hits in an event by reading all the valid values into a list, sorting the list, and returning a list of the indices of the TOF spectra associated with the sorted values.

<table>
<thead>
<tr>
<th>Original Spectra</th>
<th>Values (ns)</th>
<th>Returned Index List</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOF_hit_1</td>
<td>75.23</td>
<td>2</td>
</tr>
<tr>
<td>TOF_hit_2</td>
<td>72.56</td>
<td>1</td>
</tr>
<tr>
<td>TOF_hit_3</td>
<td>84.29</td>
<td>3</td>
</tr>
</tbody>
</table>

*Table 3: An example of time ordering*

After time ordering the TOF spectra for an event, a sorted list of related indices existed for the event, so it was a simple matter to write more processes to implement this sorted index list to time order every other hit spectra in the event.

We were curious to find out how wrong the previous ordering had been, so I wrote another process to record the number of times the sorting script had to make a index changes for an event.
Figure 6 tells us that over 100,000 of all hits were ordered correctly, however the majority of the events in this plot are of multiplicity one. Unfortunately, this graph doesn’t really give us an idea of how far MoNA’s original ordering is from the correct time ordering; how far an index had to be moved by the sorting script.

To plot fig. 7, I wrote a process to count the number of times an index was moved N spaces over an entire run. As we see, the majority of indices only needed to be moved by one or two spaces, so MoNA’s original timing isn’t as bad figure 6 might lead us to believe.
6. Neutron Events

All events begin with a neutron (or several neutrons, but let’s not complicate matters just yet) entering MoNA and colliding with a something (usually $^{12}\text{C}$ or $^{1}\text{H}$) somewhere in the interior and knocking a proton out of the molecule. The neutrons in which we’re interested were accelerated to somewhere around 50 MeV$^6$, so in colliding they could lose anywhere from almost nothing to all of their original 50 MeV, depending on the collision.

The amount of energy lost to the expelled proton in a collision depends largely on the type of incidence; in a head on collision with $^{12}\text{C}$, a neutron will lose all of its energy, but if incidence is at an angle the neutron will lose only a part of its energy. It’s entirely conceivable that a single neutron will interact 5 or 6 times within MoNA; it just needs to get lucky in its collision pattern. Remember; the molecules composing MoNA are stable, so it’s not as though the neutron is going to be absorbed.

Because of this mechanism, the second hit in any event is going to be either a proton or neutron. For a multiplicity two event (in which there are only two hits) it’s almost certainly a proton, because if there are only two hits, and the first is a neutron, then the first interaction must have been a head on collision with $^{12}\text{C}$, so the neutron lost all of its energy in the first hit to the proton in the second hit.

A similar process typifies the interaction of multiple incident neutrons with MoNA. This is the crux of our problem, since MoNA detects neutron reactions, not neutrons. Unfortunately, neutron-MoNA interactions and proton-MoNA interactions look a great deal alike, so prior to determining which hits were caused by a single incident neutron and which hits were caused by multiple neutrons, we must establish some criteria for distinguishing between neutron interactions and proton interactions.

Because neutron-proton interactions play such a large part in the detection process, we classify them as NP-easy (involving one neutron and one proton per incidence) and NP-hard (involving more than one neutron and multiple protons). The object to this classification is to define our way into an identifiable species of events; once we’ve done that, we can take that species out of the whole, and what’s left will be NP-hard. Then we can define our way into an identifiable NP-hard series of events, and eventually we’ll have classified all events into something we can understand. Let’s start by looking at neutron interactions by time of flight.

7. The Neutron Peak

Since the neutrons with which we’re concerned have similar kinetic energies, they should (on average) also have similar times of flight: $k = \frac{1}{2}mv^2 = \frac{1}{2}m \frac{d^2}{t^2}$; since the distance traveled is constant, and the mass of a neutron is constant, time is the only variable, so all neutron event’s times of flight must be proportional, modulo

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$^6$ This may vary, depending on the experiment. The bulk of the data I analyzed was from experiment 05039; Breakup of $^{25}\text{O}$ into $^{24}\text{O}$ and a neutron, and these neutrons have a velocity of 50 MeV.
some constant. This being so, we postulate the existence of a neutron peak; if we were to plot the times of flights for the \(n\)th hit of all events, there should be a spike somewhere in it representing average time of incidence, depending on how MoNA calculates ToF.

Figure 8 displays plots of the first 9 TOF peak sorted hit spectra. Having obtained the location of the neutron peak from the time ordered TOF hit spectra, I modified my sorting script to return only time ordered events between 50 and 100 ns. The first hit peak is located at about 68 ns, so we would expect the second hit to be located somewhere after that in time (since the second hit is a result of the first hit):
Now that we know that the neutron peaks are moving in time, we need to know how (or if!) they are moving spatially in MoNA. We hope this will tell us what types of scattering predominate the reactions.

![First 6 Neutron Peaks in Y](image1)

The neutron peak for Y1 is located in the center of the detector (remember, Y is the vertical axis); this is not surprising, since the beam is centered there. In subsequent Y hits, we expect that the peak will broaden and flatten out, as it does. In Z, we expect there to be a fairly well defined peak, and we expect this peak to move from the front of MoNA towards the back. Since this peak tends to the back of MoNA in time, we should not expect to see much back scattering.

Which is exactly what happens. So we have a neutron peak that’s moving in time, flattening out vertically, and moving into MoNA.

![First 6 Neutron Peaks in Z](image2)

Having shown that the neutron peak moves in Y and time as well as in Z in time, we’d like to know how the peak moves in Y with respect to Z. This should tell us where the majority of the interactions occur, and once we know this, we can begin...
to classify events as being caused by multiple interactions of a single neutron or by interactions of several neutrons.

8. Putting it All Together

At this point, we have time sorted TOF spectra, we know that the first hit inside the neutron peak is very probably the beginning of a neutron event, and we know that the neutron peak is moving in time and spreading out as it moves into the detector; so we expect lower multiplicity events to completely react closer to the front of MoNA and higher multiplicity to stop farther back in MoNA.

At this point, we will turn from examining the spatial and temporal behavior of the interactions to looking at the energy deposited in a hit. If we know how much energy was deposited in a hit, we can compare this quantity with the original energy of the neutron (beam velocity, in this case) and use the difference to classify the type of collision that occurred in the reaction. Once we know what the collision was like, we can confine the scattering angle of the neutron and the proton to the region typified by the collision and predict where and with what energy the next hit should occur.

We will test our predictions by measuring the deposited charge in the hit. For a neutron event with multiplicity 2, where this particular event was triggered by a neutron running head on into a carbon and the expelled proton reacts completely in the second hit, we should see a deposited charge in hit two that matches the deposited kinetic energy of hit one nearly exactly. We will expand this model for higher multiplicity events; this is merely a matter of allowing several hits to be neutrons, and following the expelled particles till they react completely. Since the neutron cones/peaks are fairly well defined up to hit 6 for the $^{25}\text{O}$ data, we do not anticipate that a significant number of particles will leave the detector before interacting completely, allowing us to cut down on the error in tracing complete event reactions.

![Y1 vs Z1 Neutron Cone](image_url)

*fig. 12: y (horizontal axis across the page) vs z (axis into the page) vs counts (vertical axis) for the first Y and Z neutron peaks.*
9. Acknowledgements

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