Photon and Neutron Differentiation and Evaluation ADC Board Testing

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This summer, I accomplished two tasks: testing an evaluation ADC board and performing data analysis to differentiate between photon and neutron waveforms. This work relates to two ongoing experiments that are being worked on at Michigan, $JSNS^2$ and K0TO.

Background

The $JSNS^2$ experiment, or the J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source, is an experiment looking for evidence of sterile neutrinos. We have evidence for sterile neutrinos, a new neutrino type, based on reported imbalances in neutrino flavor in recent experiments, such as LSND. The Standard Model currently includes three flavors of neutrinos, with two characteristic oscillation frequencies that are related to the mass difference squared between the two oscillating neutrino flavors involved. Neutrino oscillation probability also depends on the length that neutrinos must travel before they can change flavors. For the current known characteristic oscillation frequencies, neutrinos must travel many kilometers before they change flavor. The reported experimental neutrino flavor imbalances indicate a third distinct characteristic oscillation frequency that is much higher than the two characteristic oscillation frequencies that we understand well. A new characteristic oscillation frequency that is higher than the two that we know about necessitates a fourth flavor of neutrino that is considerably more massive than our current three neutrinos. This high oscillation frequency also corresponds to a length on the order of 10 meters for a neutrino to change flavors. In $JSNS^2$, a beam of muon antineutrinos is directed at a liquid scintillator detector that is 24 meters away. If a muon antineutrino oscillates into an electron antineutrino, the electron antineutrino will react with a proton to produce a positron and a neutron, which will be detected in the liquid scintillator target. The liquid scintillator is doped with gadolinium to capture neutrons, but if the neutrons are not promptly captured, we need to understand how they interact with the liquid scintillator.

The K0TO experiment, or K^0 at Tokai, investigates the rare decay of the neutral long kaon, $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$. This kaon decay is ultra rare, with a branching ratio of 2.8×10^{-11} according to the Standard Model and it is also directly CP violating, which makes this decay very interesting. Charge-conjugation and Parity violating decays could be the reason for our universe's asymmetry of matter and antimatter, so investigating this decay and observing a direct CP violation will allow us to learn more about this property. The very small branching ratio of this decay means that we will need 30 billion kaons to decay before observing a single $K_L^0 \rightarrow \pi^0 \nu\bar{\nu}$ decay. This necessitates a very fast data acquisition system as well as a very thorough understanding of background sources. The actual signal that indicates that we may have our specific decay is a detection of two photons with a large imbalance in momentum. Because the decay results in a neutral pion and two neutrinos, the pion will fly off in one direction and quickly decay into two photons, and the neutrinos will fly off in the opposite direction to conserve momentum. This means that the center of energy will not be along the beamline, as it would be in other decay modes that would ultimately result in two photons, like $K^0_L \rightarrow \gamma\gamma$. In the image below, you can see how our target decay would interact with the CsI calorimeter.

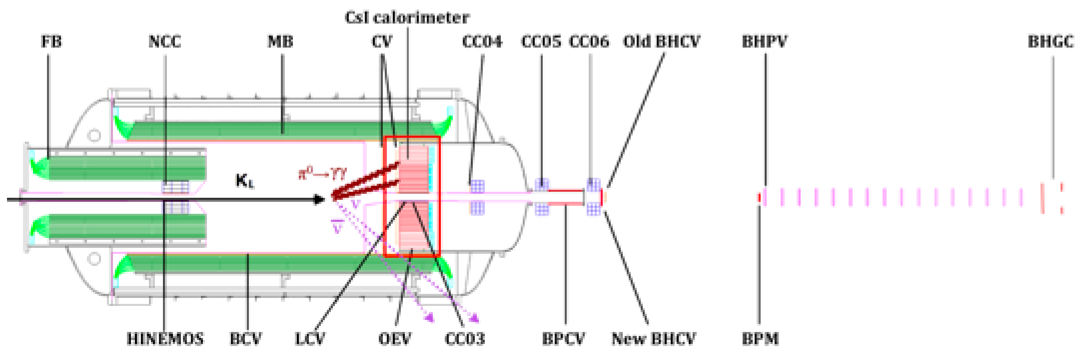

Figure 1: Side view of the K0TO detector, with a $K^0_L \rightarrow \pi^0\nu\bar{\nu}$ decay being shown inside the detector. You can see the different directions of pion and resulting photons in comparison to the direction of the resulting neutrinos.

The main detector, the CsI calorimeter, is made of thousands of cesium iodide crystals acting as a scintillator. We can tell exactly what crystal in the calorimeter is hit by particles and this location information allows us to reconstruct decay events. If there is a neutron in the detection chamber, it can hit the CsI calorimeter and then scatter and hit another crystal in the calorimeter. This single scattered neutron could be misidentified as two photons interacting with the calorimeter which would result in a false-positive signal for our specific decay mode.

<u>Project</u>

As I mentioned above, K0TO has a robust data acquisition (DAQ) system to handle the extremely large number of events necessary to observe our rare decay. The first part of my summer was spent working with an evaluation ADC board as a candidate for the design for upgraded ADCs for K0TO. ADC boards, or analog to digital converter boards, are the first step of the DAQ chain. A signal passes from the detectors to an ADC to get digitized and compressed before being analyzed by the DAQ system. The current K0TO ADC boards run at 500 MHz and are 12 bit boards whereas the evaluation ADC is a 500 MHz, 14 bit board. The extra two bits will allow for higher data resolution as well as the transfer of more information per packet of data sent through the DAQ chain. My task was to ensure that this board can take input from our phototubes and provide a good resolution waveform output.

To produce these results, we needed to accomplish two things: design a way to trigger the board to record events when there is a particle signal and condition the input signals and ensure that the input is within the dynamic range of the board. To trigger the board, we used an external trigger from an oscilloscope with an inversion circuit to produce a positive-going 1.8V signal delivered to the external trigger channel of the evaluation board. By sending the signal first through the oscilloscope, the board could be triggered promptly and observe the waveform directly after the trigger. This was all well and good using small amplitude signals from a pulse generator, but signals from our phototubes have a much larger range in amplitude that could damage the hardware on the board. This is where input signal conditioning is necessary. The dynamic range of the evaluation ADC is from -0.3V to +3.0V[1]. Signals from the phototubes can range anywhere from 1 to 8 volts in amplitude, so we needed to constrain these inputs to be under 3V. This was achieved by using a single to differential signal conversion board along with two diodes arranged going opposite directions in parallel. The differential output is split into negative-going and positive-going components, with each diode constraining one component of the differential signal. If a signal was greater than about 2V or under 0V, the diodes would saturate and effectively 'clip' the signal to maintain about 2V amplitude. This is within the dynamic range of the evaluation board, so we were able to take data using our detectors. The test was successful, and the FPGAs and design of the evaluation board will be implemented in future ADC design.

During the second half of my summer, I worked with differentiating photons and neutrons from a californium-252 source with two different setups, one using a liquid scintillator and the other using a CsI crystal. Californium is a fission source, so it decays into photons and neutrons among other debris at the same time. To differentiate photons and neutrons, we used a setup with two detectors, shown in the image below.

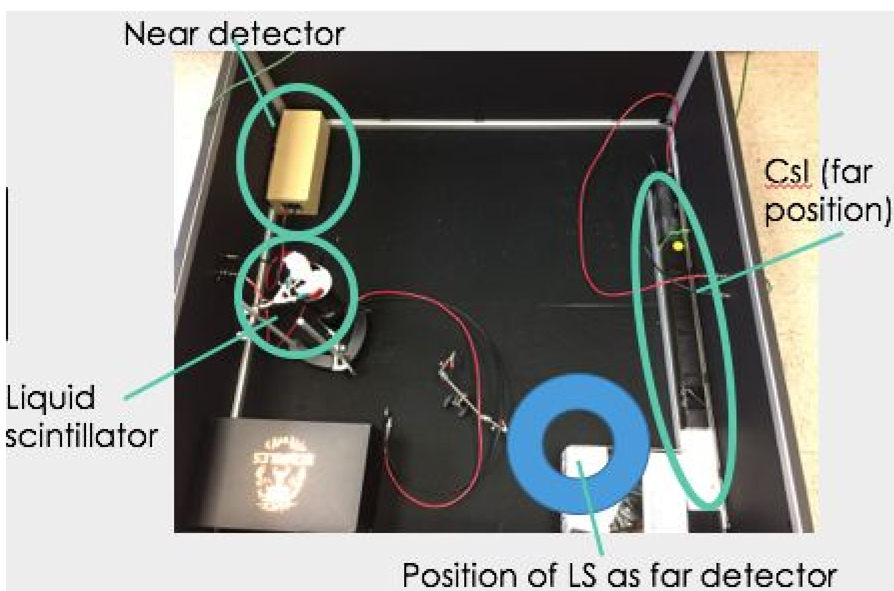

Figure 2: Experimental setup with labeled near and far detectors. In this image, the CsI crystal was acting as the far detector, so if the liquid scintillator was acting as the far detector, it would be placed where the thick blue circle indicates.

There are two methods that we can use to differentiate photons and neutrons: time of flight and waveform shape analysis. The most straightforward differentiation method in our setup is time of flight. Because the two detectors are placed about a meter apart, and photons travel faster than neutrons, there is an inherent and large time difference between photons and neutrons reaching the far detector. Photons travel at the speed of light, so it takes a photon about 3ns to travel 1 meter. Neutrons are massive, and a 2MeV neutron travels at about 2 x 10^7 m/s so it takes a neutron about 50ns to travel 1 meter. Waveform shape analysis is a more complex method, and our experimental setup was great for developing this differentiation method. Using our setup, we were able to tag events based on their time of flight as photon or neutron events. These tags allowed us to find average waveforms for photons and neutrons and compare these average waveforms to see if we could differentiate the particles based strictly on waveform shape. We determined that photons have a smaller and shorter tail compared to neutrons, which have a longer and larger tail. By defining the tail of the waveform to be any shape 20ns after the initial waveform peak, we can create a ratio Q defined as the area under the tail of the waveform divided by the total area of the waveform as a way to differentiate photon and neutron pulses.

Results

I tested the evaluation ADC board with inputs from our phototubes using Na-22 as a source, and we were able to capture waveforms, so the evaluation board design and FPGA chips can be used in future ADC upgrades. The resolution of waveforms is good with minimal noise.

By performing time of flight and Q value analysis on a 2000 spill data set using the liquid scintillator setup, I was able to differentiate between photons and neutrons based on waveform shape. Below is the average waveform graph as well as the Q value distribution graph.

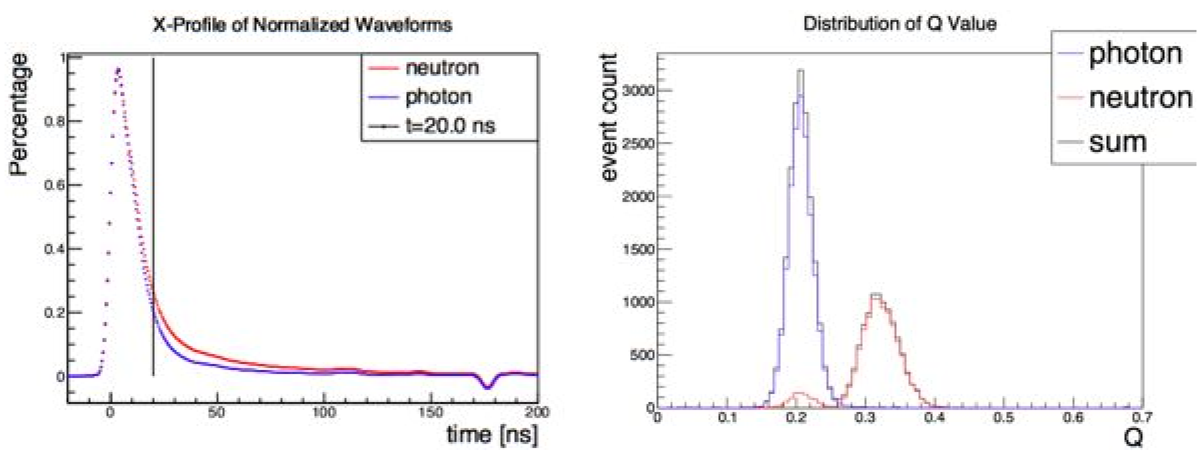

Figure 3: Average waveforms of photon and neutron events are shown on the left, with a line indicating where we define the tail of the waveform to begin. On the right, the Q value distribution for photon and neutron tagged events is plotted.

Based on the distribution graph on the right above, I designed a cut based on Q to remove neutron events from the set. By applying a cut at Q = 0.26, 99.3% of neutron events can be removed from the data set while we retain 99.9% of the photon events. This is an efficient cut for the liquid scintillator setup to differentiate between the particles.

In the CsI setup, things were a bit more complicated. Waveforms in the liquid scintillator setup appeared to look like smooth asymmetric Gaussian curves, but the CsI waveforms appeared to be either a sharp peak with no characteristic exponentially decaying tail or very noisy with peaks spaced about four samples apart. The reason for these more complicated waveforms is due to two things: CsI emitting exclusively Cherenkov radiation and reflections within the crystal. We discovered that CsI produces photons through Cherenkov light, rather than scintillation light that we were used to in the liquid scintillator. The scintillation time constants allowed us to fit the previous set of data and extract parameters from fits. The noise in the waveform that appeared to be spaced roughly four samples apart is most likely from reflection of the light off the surfaces of CsI. The ADC samples every 2ns, and a signal would take about 8ns to reflect from the phototube down the length of the crystal and back to the phototube. Because the Cherenkov radiation produced either steep and narrow peaks or very noisy reflection tails, it was difficult to perform the same analysis process on this data set because we could not properly fit the waveforms. Below is the graph of the average photon and neutron waveforms after doing time of flight analysis.

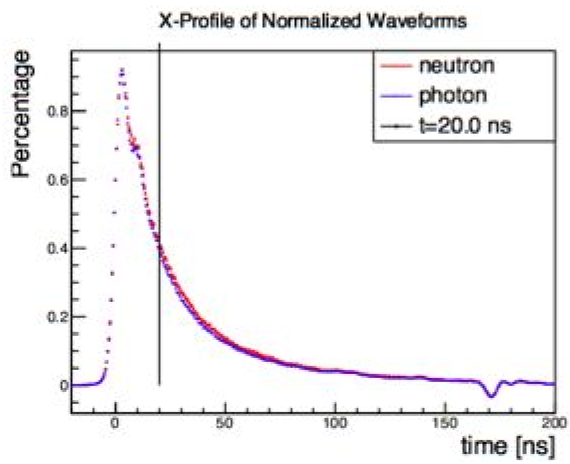

Figure 4: Average waveform shapes for photon and neutron events in the CsI data set based on time of flight tagging.

It is plain to see that these waveforms do not have very distinct shapes like what we saw in the above graphs of the average waveforms in liquid scintillator. Again, this is a result of bad waveform fitting due to the crystal reflections. Because we cannot resolve distinct waveform characteristics based on the current fits, Q value analysis is not a reliable way to differentiate between photons and neutron using a single CsI crystal setup.

Overall, this has been a great summer experience. It was my first exposure to high energy physics and I learned a lot of great programming and data analysis skills. High energy physics is

an incredibly active and exciting field and I am grateful that I had the opportunity to learn about K0TO and JSNS[2]. I want to thank my advisor, Myron Campbell, for his endless support this summer as well as the other members of my lab group, Dr. Monica Tecchio, Dr. Brian Beckford, Stephanie Su, Melissa Hutcheson, Yongyi Wu, Molly Taylor, and Kristin Dona for answering immense amounts of questions that I had throughout the summer. It has been a pleasure working with these people and I sincerely appreciate all of the effort that was put into making my summer great.

Works Cited

1) Texas Instruments. ADS5XJ6X Evaluation Module User's Guide. 2016.