The MuSun Experiment: Electronics Energy Resolution

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Abstract

Understanding the process of muon capture on the deuterium atom will provide information concerning fundamental astrophysical processes such as the proton-proton fusion which takes place in our sun. The MuSun experiment aims to measure this capture rate to within 1.5% precision. A muon beam is directed into a time projection chamber (TPC) filled with deuterium which acts as an ionization chamber, allowing the muons' paths to be reconstructed. Comparing the decay rate of positive and negative muons in deuterium, the rate of muon capture can be extracted[1]. When a muon decays, energy, via ionization electrons, is deposited on to a pad plane and converted into an electronic pulse which is sent through an electronics chain for amplification and shaping. In this project, the energy resolution of this electronics chain was studied using experimental data, LabVIEW[2], theoretical analysis, and SPICE[3] simulations.

Introduction

Created either in the interaction of cosmic rays with heavy particles in the upper atmosphere or in large accelerators, muons are one of the fundamental particles predicted by the standard model. By understanding their reactions with various other particles and atoms, much can be learned. In particular, studying the capture of muons by deuterons can shed light on various astrophysical processes including the proton-proton reaction, the dominant source of energy in the sun[4]. Both are mediated by the strong interaction effect which is not well understood. In this project, the energy resolution of the MuSun electronics chain is investigated.

Muon Decay and Muon Capture

Muons have a relatively long lifetime (on the order of 10^{-6} seconds), meaning that many are able to reach Earth before decaying. In the decay process, a product electron is produced, along with 2 neutrinos. When a muon interacts with deuterium gas, there is a possibility of it being captured by a deuteron. In this capture process, 2 neutrons and a neutrino are produced, as shown in figure 1.

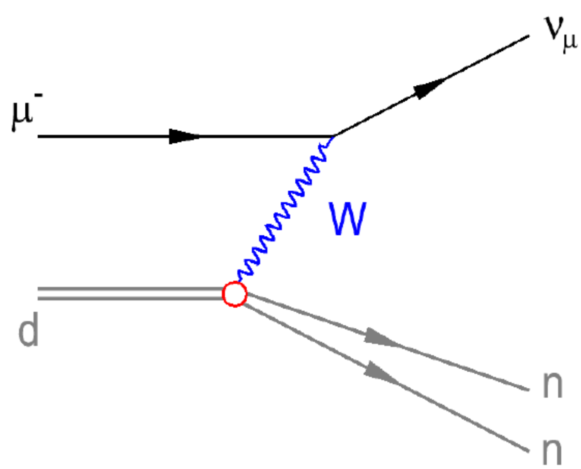

Figure 1 – When a muon is captured by a deuterium atom, 2 neutrons and a neutrino are produced. This process is mediated by the W boson.

By comparing the decay rates of both positive and negative muons in deuterium gas, the muon capture rate can be extracted. In a vacuum, the two decay rates should be identical, but in deuterium, the negative decay rate is slightly smaller due to the possibility of muon capture. The difference between these 2 rates is equal to the muon capture rate, as seen in figure 2[1].

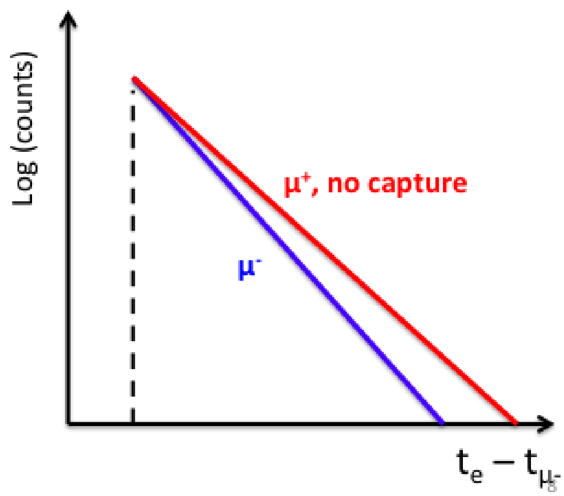

Figure 2 – By comparing the decay rates of positive and negative muons in deuterium gas, the negative muon capture rate can be extracted. The negative muon decay rate is smaller due to the possibility of muon capture.

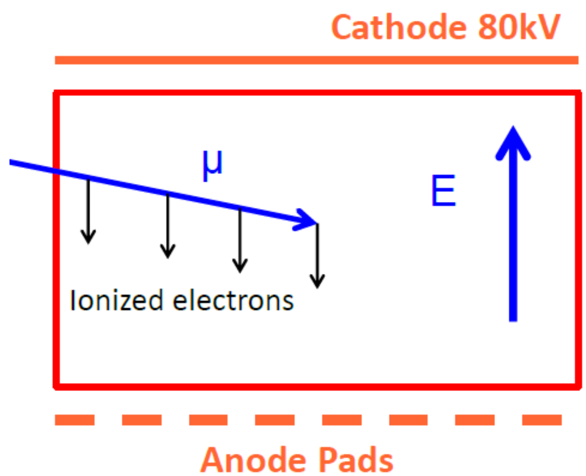

Figure 3 – A high voltage applied to the cathode of the TPC causes ionized electrons, created by the path of a muon, to drift downwards towards the anode pads with a drift speed of about 1/2 cm/μs, causing a detectable pulse.

Experimental Setup

In this experiment, a muon beam is directed into a time projection chamber (TPC) filled with deuterium gas, which acts as an ionization chamber. The TPC consists of an anode pad plane and a cathode with an applied high voltage of 80 kV. The TPC has an active volume of 10x12x8 cm^3[1]. Throughout its trajectory within the TPC, a muon ionizes many deuterium atoms. The electric field caused by the potential difference between the anode and cathode causes these ionization electrons to drift downwards towards the anode at a speed of about 1/2 cm/μs, relatively slowly, as shown in figure 3. In this process, a detectable charge is deposited onto the pads which can be read out using waveform digitizers or a flash ADC.

Pulses from the pad plane are first sent to a preamplifier for initial shaping and amplification. After the preamplifier, the signal is sent through an Ortec 673 spectroscopy amplifier and gated integrator[5], before being read in by a custom designed flash ADC.

Preamplifier

In radiation detectors, preamplifiers are used to collect charge deposited within the detector. They are used as an interface between the detector and the following electronics chain. A preamplifier in a charge sensitive configuration, such as the one used in this experiment, integrates the transient current it receives and then converts this signal into a proportionally sized voltage step. All of this is done while degrading the signal-to-noise ratio of the original signal as little as possible[6]. In this project, two different preamplifiers were tested: a custom designed MuSun preamplifier and an Amptek A250 preamplifier board[7].

Shaping Amplifier

After being sent to the preamplifier, the signal is then processed by an Ortec [5] shaping amplifier. The shaping amplifier is used to amplify the signal an appropriate amount (the flash ADC accepts signals up to 1V in amplitude) as well as to shape it (high and low pass filters are used to eliminate excess high and low frequency noise).

The Ortec also includes a pile-up rejector to minimize distortion caused by pulses received almost simultaneously [5]. The adjustable shaping time of the amplifier allows for different processing of the pulses. In general, in order to obtain good energy resolution, a long pulse width (long shaping time) is necessary. On the other hand, in order to accommodate high counting rates, a short shaping time is necessary[6]. A shaping time must be chosen which allows for a good energy resolution while still able to handle the experimental counting rate.

Electronic Noise and Energy Resolution

Electronic noise present in a system can make determining the exact voltage of a signal difficult and limits the degree to which one can tell different signals apart. The energy resolution of a circuit is a measure of how accurately signals can be differentiated. For this project, the shaping amplifier output was sent into a custom designed flash ADC, whose output was then integrated and analyzed using ROOT[8] programs. Energy resolution was calculated as $EnergyResolution(keV) = \frac{InputEnergy}{Baseline-Mean} * RMS$, where $InputEnergy$ is the energy injected into the system via a test pulse, $Baseline$ is the background noise level, $Mean$ is the location of the peak, and RMS is the RMS spread of the signal.

In order to calculate input energy, the circuit in figure 4 was used. A square pulse of known amplitude is sent first through a voltage divider, and then through a large capacitor. This capacitor allows for a conversion between voltage and charge, from which the number of injected electrons can be found. This value is then multiplied by 36.5 eV, the ionization energy per electron in hydrogen, giving the amount of injected energy. After noting the output amplitude of the pulse, the large capacitor is replaced by a much smaller one (about 1-2 pF) and an input pulse chosen such that the same output amplitude is observed. In this way, a large capacitor (whose value can be more precisely measured) is used to calculate injected energy, and then a smaller capacitor (which contributes less noise) can be used in the experiment.

Experiment

For this project, different parameters were changed on the 2 preamplifier boards to explore their effects on the energy resolution. In particular, the effects of protection diodes and capacitive loads were explored using varying methods. Experimentally, data was taken using the flash ADC. In addition, noise curves were generated from the experimental data, using LabVIEW [2], doing a theoretical analysis, and creating a SPICE [3] model of the circuit.

Data

In order to facilitate collecting the cleanest data possible, a “clean” setup needed to be put together. It was found that both preamp boards are very sensitive to grounding, so all components were grounded together (including the preamp, power supply, function generator, oscilloscope, and flash ADC). In addition, the preamp was very prone to pick-up. In order to reduce the presence of unwanted signals, the boards were placed in a Faraday cage with both bottom and top covers. Using this clean setup (with no additional load capacitance), the best obtained values of energy resolution were 12 keV for the MuSun board and 6.7 keV for the Amptek board, in comparison with the 60 keV that was previously achieved.

Using this ideal setup, the effect of capacitive loads on the energy resolution was calculated for both the MuSun and Amptek boards using small capacitor chips attached to pins at the preamplifier input. Understanding the effect of capacitive loads on the energy resolution is important as there are noise sources which are proportional to capacitance. This understanding is particularly important as in the experimental setup, a cable

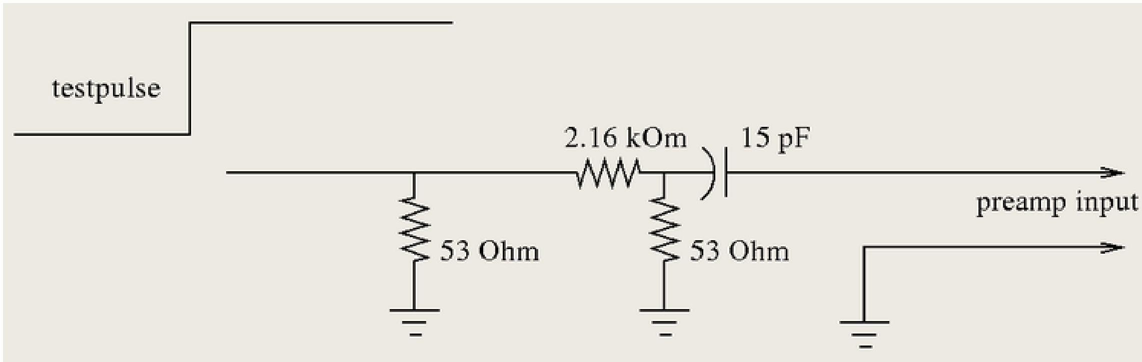

Figure 4 – The circuit used to calculate input energy. A capacitor allows for conversion between voltage and charge and then a known constant can be used to translate this value into an injected energy.

connecting the TPC to the preamps was found to act as a large capacitive load. How this cable (and other sources of input capacitance) affects the energy resolution needs to be understood in order to make decisions regarding the setup. Capacitive load curves for both boards can be seen in Appendix A, figure 5. The 2 boards have similarly shaped curves, but the MuSun board's resolution is worse by about a factor of 2, a phenomenon which is still not fully understood.

Not only can these curves be used to predict the effect of a capacitive load on energy resolution, they can also be used as an indirect way of measuring capacitance. By attaching an object of interest to the preamp input as a capacitive load and then measuring the energy resolution, the capacitance of the object can be found by referencing this plot. Estimates made in this way have been verified using a capacitance meter.

Another aspect that was explored with experimental data is the effect of protection diodes on the energy resolution. In order to protect the electronics from sparking that may occur within the TPC, protection diodes are normally placed at the input of the preamplifier. Using the flash ADC, these protection diodes were found to add 3-4 keV to the energy resolution of the system (this is the same as the effect of a 50pF capacitive load). For this reason, other protection possibilities, which would have less of an effect on energy resolution, are currently being considered.

Noise Curves

As previously mentioned, the Ortec shaping amplifier has a selectable shaping time. The shaping time of an amplifier is a measure of the time it takes a pulse to reach its maximum value. In order to have a good energy resolution, a long shaping time is necessary. In contrast, in order to deal with high counting rates, a short shaping time must be used. The shaping time of an amplifier must be chosen such that good energy resolution can be achieved while still dealing with the counting rates necessary for the experiment.

An ENC (equivalent noise charge) curve can be used to find an ideal shaping time. ENC curves plot noise (as electrons RMS) as a function of shaping time. Using a LabVIEW program which calculates the power spectral density (PSD) of a signal, experimental ENC curves were produced by integrating the PSD and then multiplying by the transfer function of the shaping amplifier and a normalization constant. An experimental noise curve for the Amptek board can be seen in Appendix A, figure 6. This curve implies an ideal shaping time of slightly shorter than 1 μs, matching what was found experimentally (energy resolution measurements were taken using different shaping times). An ENC curve was also calculated theoretically for the Amptek board. Knowing all of the components within the circuit, the noise contributions for each were calculated and then added in quadrature. The result of this analysis also implied an ideal shaping time of about 1 μs.

SPICE Simulation

One last method was used to verify the experimental and analytical data previously presented. A SPICE[3] model was created of both the MuSun and Amptek electronics chains, incorporating noise models of various components provided by the manufacturers. Using these SPICE models, ENC curves and capacitive load plots were calculated. Power spectral density plots were also produced. All of the above were found to be within acceptable agreement of the experimental and analytical data.

Conclusions

Energy resolution data was provided for both the MuSun and Amptek preamplifier electronics chains used in the MuSun experiment. Energy resolution was made better by a factor of greater than 5 from previous values. Data was also presented exploring the effects of capacitive loads on both boards. Based on these measurements, discussions have begun about better placement of the TPC and preamplifier boards in order to reduce the length of necessary connection cable (which was found to be a large capacitive load).

Future Work

In continuing to work on improving the electronics of the MuSun experiment, the reasons for the disagreement between the MuSun and Amptek boards needs to be better understood. The MuSun board should be functioning as well as the Amptek board, yet it has been shown that it is worse by a factor of 2. In addition, more work needs to be done on analytical modeling, particularly on understanding the effects of protection diodes. This modeling will help in making a final decision about what protection mechanism to use in the experiment. Finally, more work needs to be done in ensuring better agreement between different methods of testing experimental energy resolution, although it is encouraging that the different methods currently provide similar data.

Acknowledgements

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Appendix A: Experimental Figures

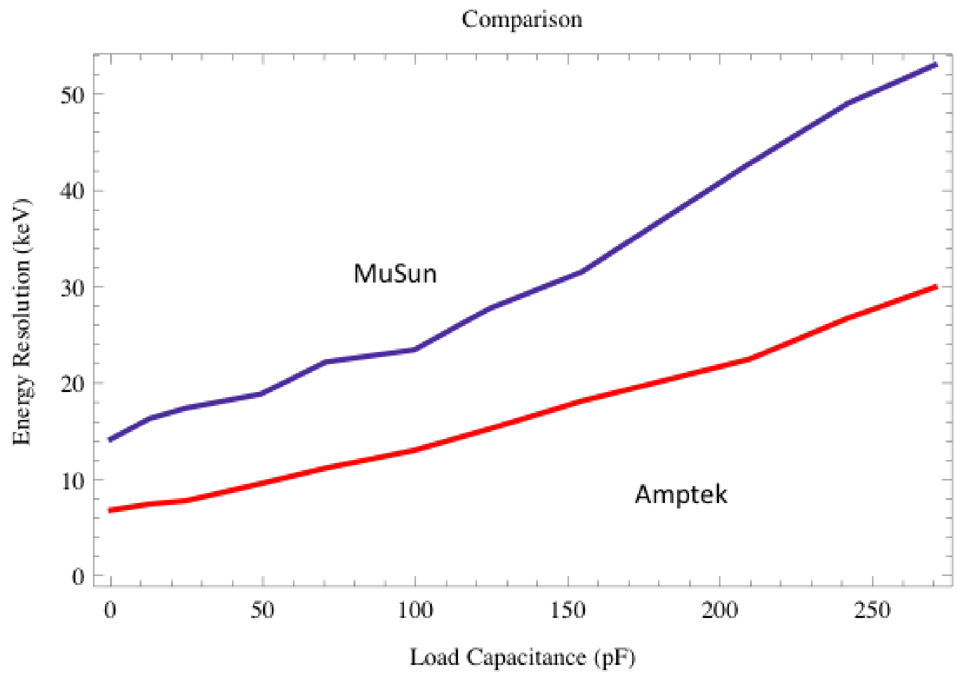

Figure 5 – A plot of energy resolution as a function of capacitive load for the MuSun (blue) and Amptek (red) boards. The two curves have similar slopes, but the MuSun board's resolution is worse by about a factor of 2, a phenomenon which is not yet fully understood.

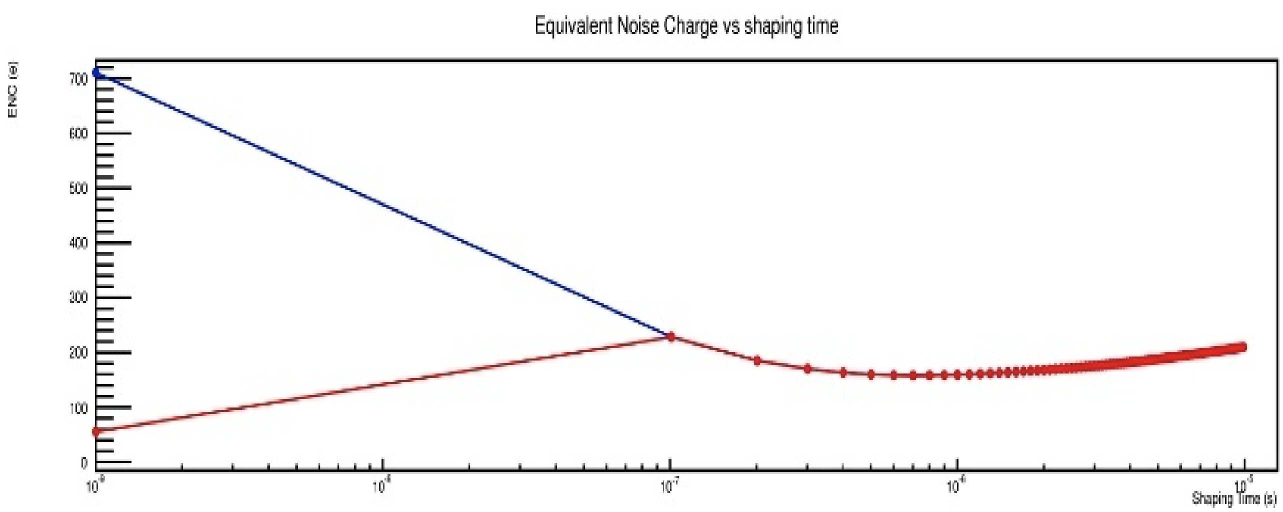

Figure 6 – An ENC curve for the Amptek board. This curve implies an ideal shaping time slightly shorter than 1μs.