Analysis of Alpha Background in SNO Data Using Wavelet Analysis

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Abstract

The Sudbury Neutrino Observatory (SNO) was a solar neutrino detector that differed from previous detectors in that it was equally sensitive to all flavors of neutrinos, which allowed SNO to obtain evidence for the oscillation of solar neutrinos. A neutrino incident on a deuteron in the heavy water used in the detector could break apart the deuteron producing a neutron. The neutron was detected by an array of proportional counters filled with 3He. The voltage vs. time, referred to as a waveform, was recorded from each proportional counter. These proportional counters were sensitive to both neutrons and alpha particles. Any alphas detected were background due to the presence of radioisotopes in the detectors. Therefore, in order to reduce the number of alpha events contributing to this background it was necessary to be able to distinguish between neutron and alpha events. Since neutrons and alphas interact differently in the detector some differences were expected in their waveforms. I attempted to eliminate confusion between neutrons and alphas by establishing a cut between them. This was done by denoising the waveforms using a stationary wavelet transform and then comparing the integrated waveforms. I will present the results of this method of distinguishing waveforms of neutrons and alphas in SNO and compare it with previous methods used.

1 Introduction

1.1 The Solar Neutrino Problem

The sun, as it is currently understood, is well described by the Standard Solar Model which treats the sun as sphere of gas in varying degrees of ionization. According to this model, the sun generates its power by nuclear fusion. This model predicts several fusion reactions, shown in Figure 1, which are known to produce electron neutrinos. It also predicts the production of several unstable fusion products which also produce electron neutrinos in their decays. These neutrinos would be emitted isotropically so the neutrino flux arriving at the earth can be calculated. A measurement of the flux of neutrinos hitting the earth would give insight into the reactions going on in the sun.

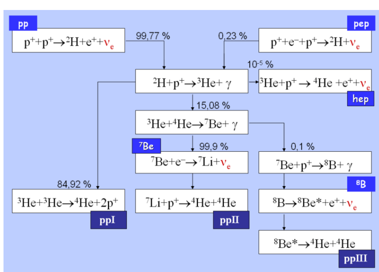

Figure 1: **Primary Neutrino Producing Fusion Reactions in the Proton-Proton Chain**

The first experiment designed to detect these solar neutrinos was the Homestake experiment designed by Raymond Davis and John Bahcall which ran from 1970 to 1994. The experiment did detect solar electron neutrinos, but the measured flux was approximately one-third of the predicted amount. Given that it is difficult to detect neutrinos, it was initially assumed that an error had been made in the detector. However, further scrutiny of the Homestake device as well as results from other experiments including SAGE in the Soviet Union, Kamiokande in Japan, and GALLEX in Italy confirmed these results. All the experiments agreed in measuring one-third to one-half of the predicted electron neutrino flux.

Attempts were then made to alter the Standard Solar Model by adjusting certain parameters such as the temperature of the sun to bring the predicted neutrino flux into agreement with measurements. Further work in helioseismology and neutrino spectroscopy, however, indicated that the solar temperature was the same as previously assumed which prevented changes in the solar model from accounting for the neutrino deficiency. This in turn showed that the problem must be something intrinsic to the neutrinos. One proposed theory, called neutrino oscillation, claims that neutrinos created with a certain lepton flavor can oscillate between different flavors as it propagates. If this were true the neutrino shortage could be caused by electron neutrinos changing into tau or muon neutrinos as they traveled to earth since detectors up until this point had been almost exclusively sensitive to electron neutrinos.

1.2 The Sudbury Neutrino Observatory

The Sudbury Neutrino Observatory (SNO) was the first neutrino detector built which was equally sensitive to all three flavors of neutrinos. The detector was sensitive to all neutrinos over 2.2 MeV, these neutrinos come not from the proton-proton reaction in the sun, but from the decay of Boron-8 to Beryllium-8 as given by the following reaction

$$B^8 \rightarrow Be^8 + e^+ + \nu_e$$

The neutrinos created in this reaction have a continuous spectrum of energies that extend up to 15 MeV making these easier to detect, albeit much rarer than proton-proton reaction neutrinos. SNOs sensitivity to all flavors of neutrinos allowed it to measure the total flux of solar neutrinos and compare the results with the predicted number of electron neutrinos produced to directly verify the Standard Solar Model and indirectly give evidence for neutrino oscillation.

SNO was located in the Creighton Nickel Mine near Sudbury, Ontario, Canada. It is located 2092 m underground in order to minimize cosmic ray background. The body of the detector consisted of a large acrylic sphere 12 m in diameter filled with heavy water (D_2O). The sphere was suspended in normal water for buoyancy and for additional radiation shielding. A schematic overview is given in Figure 2. A series of proportional counters filled with Helium-3 was seeded throughout the body of the detector and an array of photomultiplier tubes surrounded the sphere.

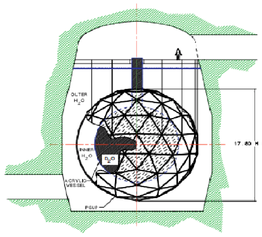

Figure 2: **Schematic Overview of SNO**

Heavy water was used to make the detector sensitive to all neutrino flavors. An incoming neutrino can interact with a deuteron according to any of the following reactions where $_x$ is any flavor of neutrino.

$$\nu_x + d \rightarrow p + n + \nu_x \quad (NeutralCurrentReaction)$$

$$\nu_e + d \rightarrow p + p + e^- \quad (ChargedCurrentREaction)$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (ElasticScattering)$$

The charged current reaction was sensitive only to electron neutrinos. The neutral current and scattering reactions were sensitive to all flavors. Comparing the flux of electron neutrinos to the flux of total neutrinos directly tested the idea that electron neutrinos being produced in the sun changed flavors before being detected at SNO. The elastic scattering reaction can be used to measure the direction from which the neutrino came in order to confirm that the neutrinos originated from the sun.

The neutral current reaction was measured by detecting the neutron released. D_2O has a low cross section for thermal neutrons so these neutrons moved relatively freely through the D_2O until interacting with the proportional counters. A schematic overview of the proportional counters is given in Figure 3.

The proportional counters were filled with Helium-3 for several reasons. Helium-3 has a large cross section for neutron capture which makes it a good choice for neutron detection. In addition to this, Helium-3 can be easily purified to ensure that fewer radioactive impurities contribute to the background signal. A neutron can interact with the Helium in the counters according to the following equation

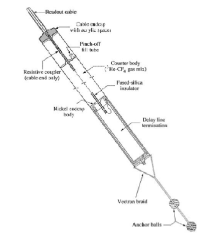

Figure 3: **Schematic Overview of the Neutral Current Detectors**

$$He^3 + n \rightarrow p + H^{3+}$$

The resulting proton-triton pair cause a cascade effect as they ionize the gas. The ionized electrons then move towards an anode wire at the center of the counter producing an electrical signal on the anode. The signal is run through a logarithmic amplifier resulting in a logged voltage vs. time output signal which we will call a waveform, Figure 4.

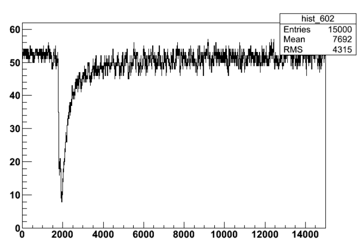

Figure 4: **An example of a logged voltage vs. time waveform recorded by an NCD**

1.3 Sources of Background Signal

It was estimated that SNO would detect approximately 3000 solar neutrinos per year. Given the relatively small number of counts it was crucial to minimize any background. The primary source of background for such a detector on the surface would be cosmic muons. At the surface the cosmic muon flux is approximately $1.5 * 10^7 muons/day * m^2$ which would completely overwhelm the neutrino signal. By placing the detector deep underground, however, the cosmic muon flux is reduced to approximately $0.6 muons/day * m^2$ corresponding to 70 muon events per day. An array of outward facing photomultiplier tubes was used to detect these incoming muons in order to give them a time tag to prevent them from being confused with a neutrino event.

An additional source of background would be from radioisotopes in the detector. Uranium-238 and Thorium-232 isotopes and their daughter products were of particular concern as these can produce neutrons which would be indistinguishable from neutrons produced from neutrino event. To minimize this problem, the detector was constructed out of ultra pure materials. The materials used were designed with a goal of only one false neutron event per day corresponding to Uranium and Thorium concentrations of $4.5*10^-14g/g$ and $3.7*10^-15g/g$ respectively in the D_2O.

The presence of trace amounts of Polonium-210 in the proportional counters also contributed an alpha background. Since the cascade effect in the counters is triggered by charged particles an alpha can give a false signal. In order to minimize this background, it was necessary to find a method of distinguishing the waveform of an alpha particle from that of a neutron induced proton-triton event. Several methods have been tried to distinguish the waveforms with the best method eliminating 98% of alpha events while retaining 74.78% of neutron events. Our efforts focused on attempting to find a better method of distinguishing alphas from neutrons.

2 Methodology

2.1 Wavelet Denoising

The waveforms collected needed to be denoised before we could analyze them. To do this we extracted the data from the ROOT source file and then did the denoising using a discrete stationary wavelet transformation. The wavelet transformations were done using the open source Python packages WavePy and Numpy. Each waveform was broken into a background region and a signal region. The background region was taken to be the points in bins [0,1024] while the signal region was the remaining bins [1025 15000], Figure 5.

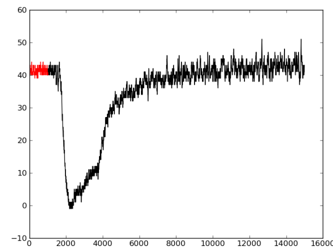

Figure 5: **An example waveform which has been split into regions of noise and signal, the first 1024 bins in red are noise the remaining bins in black are signal**

WavePy was then used to get the wavelet transform of the noise region. The maximum level of decomposition possible was used in order to capture both low and high frequency noise patterns. For each level of decomposition, the standard deviation of the transformed signal was calculated in order to set a threshold for the denoising of the signal region. The wavelet transform of the signal region was then taken, again with maximum decomposition. For each level of decomposition, we removed 99.999% of the noise components by retaining only the portions of the transformed signal which were greater than 4.5 times the standard deviation of the noise region. The waveforms taken from the ROOT file were logged. We discovered that optimal results were obtained if this denoising procedure was applied to the logged waveforms, and then applied again after delogging. An example of the results of this denoising is shown in Figure 6

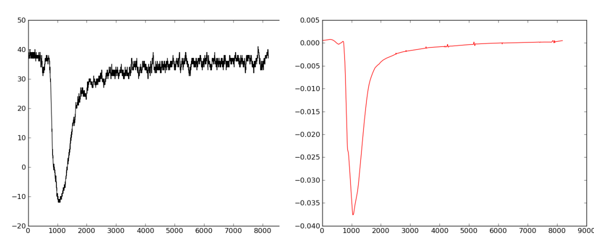

Figure 6: **An example raw waveform and the denoised waveform**

2.2 Comparison Using Integration

The denoised waveforms were then integrated over the signal region by simple addition of successive bins and then normalized by setting the largest value of the integral to one. The range of integration was determined by setting a voltage threshold. The first time the waveform crossed this threshold was taken as the lower bound for integration and the last time the waveform crossed the threshold was taken as the upper bound.

In order to compare two waveforms their integrals were compared. The maximum difference between the two integrals was used as a measure of how different two waveforms were. Several examples of integral comparisons are give in Figure 7. The goal was to be able to adjust the various thresholds in order to see if there was a combination of settings which would cause neutron and alpha waveforms to look sufficiently different that they could be distinguished. If this was possible then a certain maximum difference could be set so that if a given unknown waveform is more than that maximum difference away from a known neutron waveform then it could be assumed to be an alpha.

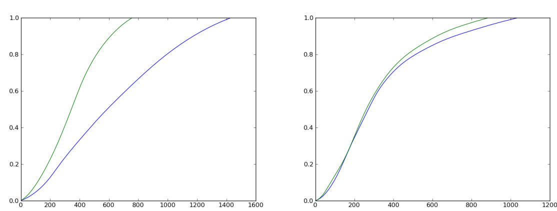

Figure 7: **The waveforms on the left are an example of a bad match while the waveforms on the right are a good match**

To determine the efficacy of this method we took three sample collections of neutrons with 683, 741, and 453 waveforms respectively, and a sample of 1431 alpha waveforms. The neutron waveforms had been compiled from a calibration of the SNO detector using a Sodium-22 source and the alpha waveforms had been compiled from simulation. The denoising and integration of each waveform was performed. For each neutron waveform the closest match to another waveform was found and recorded in a list of neutron-neutron nearest matches. For each alpha waveform the nearest neutron waveform was found. We wanted to eliminate neutrons which were indistinguishable from alphas, so a similarity threshold was then set and if the difference between an alpha and neutron was below this threshold the neutron was removed from the sample. This process was repeated until no alphas found a close neutron match. A list of alpha-neutron nearest matches was then created using the remaining sample neutrons. The neutron-neutron and alpha-neutron best match lists were plotted in a histogram, Figure 8.

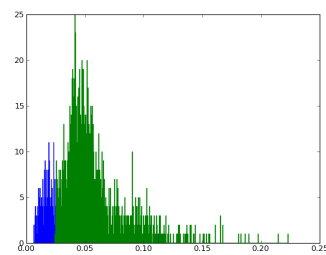

Figure 8: **This is an example of a n-n and $\alpha - n$ comparison histogram, the n-n best fits are in blue while the $\alpha - n$ fits are in green**

The histogram contained two peaks with a region of overlap in between. We then looked for the point at which to establish a cut between the two peaks which would maximize the number of alphas eliminated and the number of neutrons retained. The entire process was repeated using several elimination thresholds to find the best cut possible.

3 Results

We used the previously described comparison between all three neutron samples and the alpha sample with several different elimination thresholds. For each comparison we found the cut which retained a maximum number of neutrons while eliminating a minimum of 98% of alphas. The results are given below.

Threshold	0.020	0.025	0.030	0.035	0.040	0.050
Neutrons Kept	64.91%	68.86%	67.40%	60.88%	56.43%	48.54%
Alphas Eliminated	98.32%	98.60%	98.32%	98.74%	98.25%	98.11%
Best Cut	0.021	0.026	0.031	0.036	0.042	0.052

Table 1: **Results for neutron sample 1**

Threshold	0.020	0.025	0.030	0.035	0.040	0.050
Neutrons Kept	60.54%	65.14%	63.11%	62.97%	58.38%	49.86%
Alphas Eliminated	98.88%	98.04%	98.11%	98.04%	98.67%	98.32%
Best Cut	0.021	0.026	0.031	0.037	0.041	0.051

Table 2: **Results for neutron sample 2**

Threshold	0.020	0.025	0.030	0.035	0.040	0.050
Neutrons Kept	67.11%	65.14%	63.11%	62.97%	58.38%	49.86%
Alphas Eliminated	98.39%	98.04%	98.11%	98.04%	98.67%	98.32%
Best Cut	0.022	0.026	0.031	0.037	0.041	0.051

Table 3: **Results for neutron sample 3**

The results for each library were as we expected. For any elimination threshold we observed two peaks in the histogram with a region of overlap. We first tried the range of thresholds shown in the tables above, ranging from 0.02 to 0.05m in order to minimize the region of overlap. The best results for neutron samples 1 and 2 were at an elimination threshold of 0.025 with a cut point of 0.026. The best results for neutron sample 3 was at elimination threshold 0.02 with a cut point of 0.022. The best results for each eliminated more than 98% of alphas and retained an average of 64.04% of neutrons. The histograms corresponding to the best elimination thresholds for each neutron sample are given in

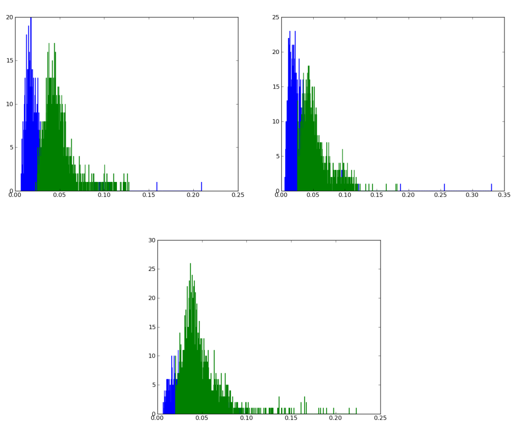

Figure 9: **Best histograms for each neutron sample n-n fits are in blue and $\alpha - n$ fits are in green**

4 Conclusion

The results of our analysis on the neutron and alpha samples demonstrate that using integration of denoised waveforms is an effective method of differentiating alpha and neutron waveforms. We were able to successfully eliminate over 98% of alphas and retain on average 64.04% of neutrons. However, compared to previous methods used which retained 74.78% of neutrons our results indicated that this method was less effective.

It is possible that the efficacy of this method could be improved by further fine tuning the various parameters used in the denoising, integrating, and comparison of the waveforms. Furthermore, while comparison of the integrated waveforms gave the best results for differentiating the waveforms, several other features such as comparison of the rise time and the width of the waveforms also showed a systematic difference between the neutrons and alphas. If the comparison of integrated waveforms is augmented by a comparison of other features which showed a systematic difference between neutrons and alphas, it may be possible to further increase improve the results.

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6 References

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