Muon-Induced Spallation in the Sudbury Neutrino Observatory

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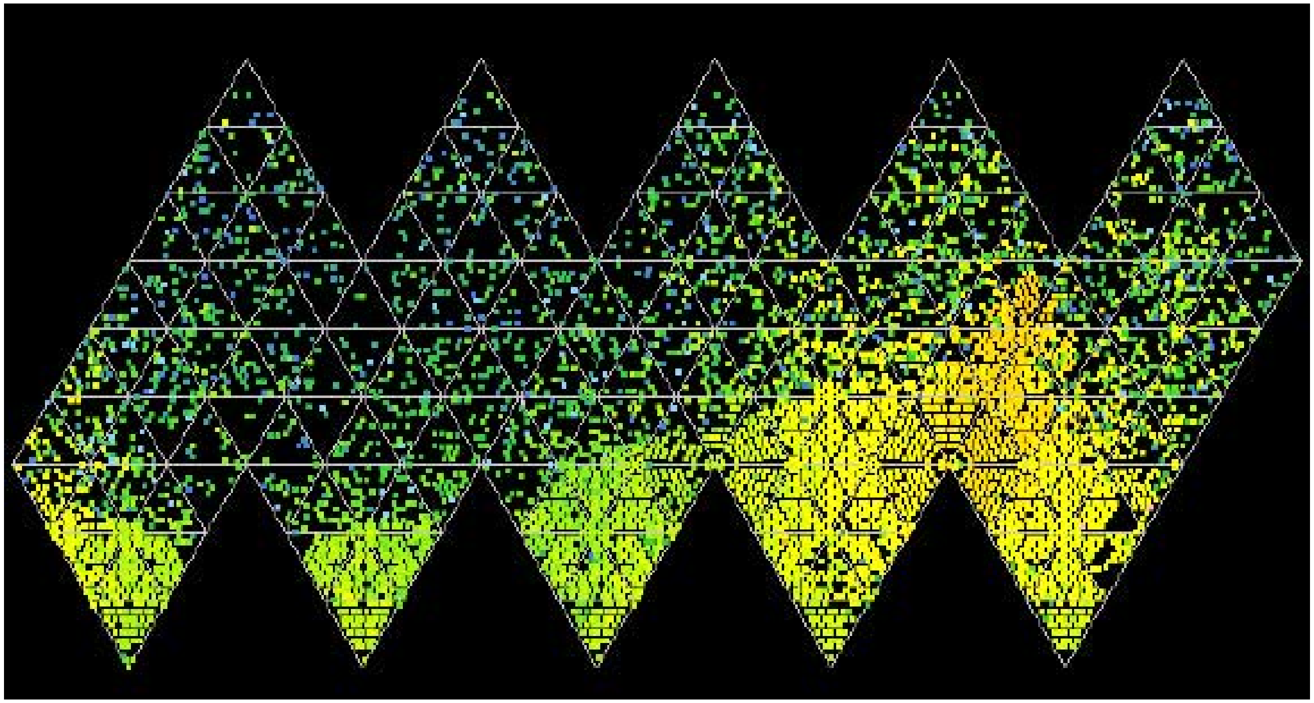


Table of Possible Spallation Products

Nucleus	Mode	Br. Ratio	Max β γ Energy (MeV)	$T_{1/2}$(sec)
^{6}He	β^-	100%	3.51	.807
^{8}He	$\beta^-\gamma$	84%	10.66(β)+0.99(γ)	.119
^{8}He	β^-n	< 16%	7.44	.119
^{8}Li	β^-	100%	16.0	.838
^{8}B	EC/β^+	100%	18.0	0.770
^{9}Li	β^-	50.5%	13.6	.178
^{9}Li	β^-n	49.5%	11.2	.178
^{9}C	EC/β^+	100%	16.5	.127
^{11}Li	β^-+1 or more n	85%	16	.0085
^{11}Li	β^-	15%	20.6	.0085
^{11}Be	β^-	55%	11.5	13.8
^{11}Be	$\beta^-\gamma$	42%	9.4(β)+8(γ)	13.8
^{12}Be	β^-	100%	11.7	.0236
^{12}B	β^-	97%	13.3	.0202
^{12}N	EC/β^+	95%	17.3	.011
^{13}B	β^-	92%	13.4	.0174
^{13}B	$\beta^-\gamma$	8%	9.7(β)+3.6(γ)	.0174
^{13}O	EC/β^+	90%	17.8	.0086
^{13}O	EC/$\beta^+\gamma$	10%	14.3(β)+3.5(γ)	.0086
^{14}O	EC/β^+	0.61%	5.1(β^+)	70.6
^{15}B	β^-	100%	19.1	.0105
^{16}N	β^-	28%	10.4	7.13
^{16}N	$\beta^-\gamma$	66%	4.3(β)+6.1(γ)	7.13

This table lists the possible unstable ^{16}O spallation products with A≤16 that decay by the production of a neutron of any energy, and/or a beta or gamma with an energy greater than 3 MeV.

Event Selection

Input Event ↓

Muon Filter

Muons are high in energy and tend to pass through the entire detector. So, we require a large energy deposit in the detector and light observed in the outward looking phototubes.

Yes→

Muon Candidate Cleaning

We require the PMT timing to be consistent with a muon track. This eliminates instrumental background.

→

Fiducial Cuts

After the muons are reconstructed, there is a requirement that the muons have an impact parameter less than 750 cm to insure a good fit.

= Muon

No ↓

Spallation Filter

Muon spallation events are relatively low in energy and have no light observed in the outward looking tubes.

They must follow within 120 seconds of a muon.

Yes →

Spallation Candidate Cleaning

We require the PMT timing and charge distributions to be consistent with Cerenkov light events. This eliminates instrumental background.

→

Fiducial Cuts

At the final stage, the spallation events are required to reconstruct inside the detector (i.e. inside 900 cm) to help remove instrumental background and to insure a good fit.

= Spallation Candidate

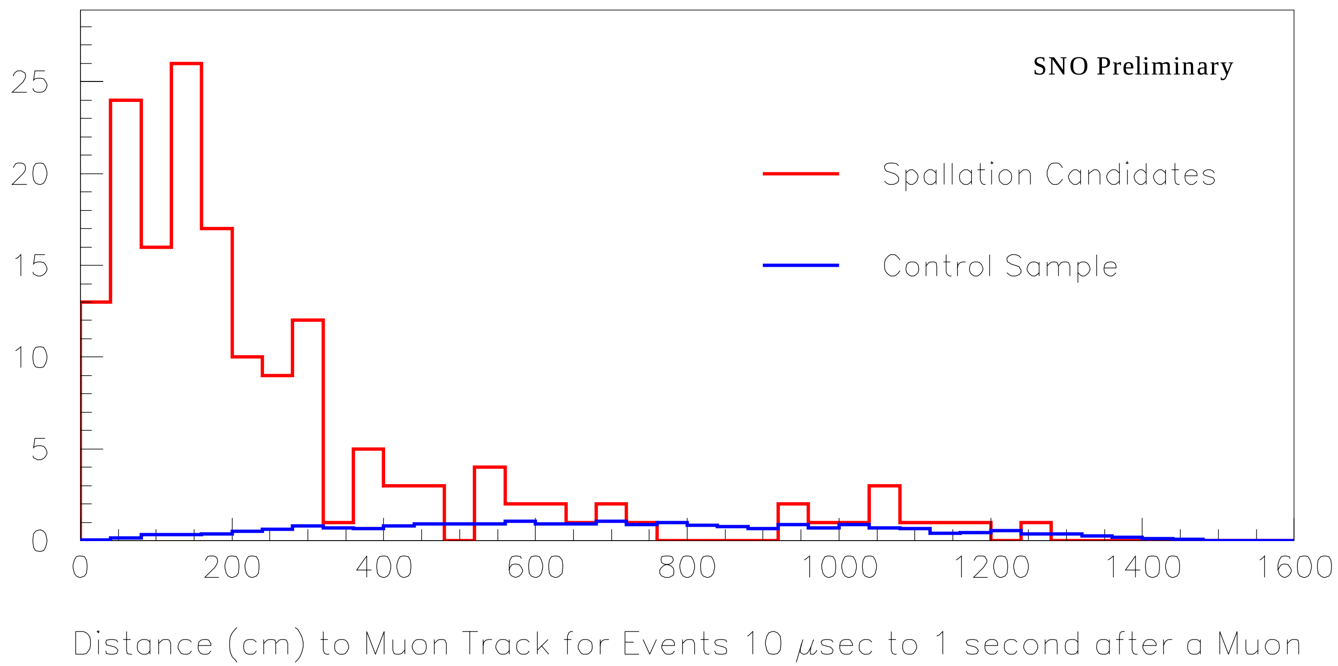
No

Reject Event ↲

Conclusions

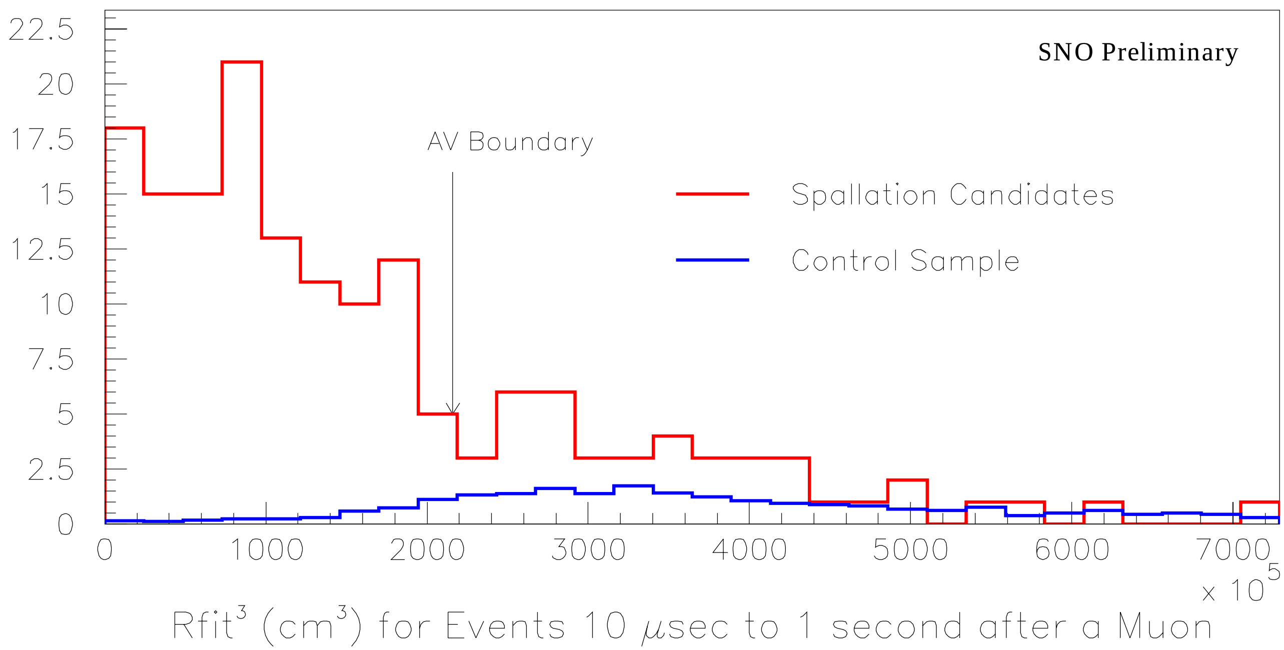
- Higher energy signal appears to be confined to the heavy water.
- The energy spectrum of the spallation products is similar to that of the ^{16}N spectrum. The energy of the ^{16}N gamma ray (6.13 MeV) is similar to the deuterium neutron capture gamma ray (6.25 MeV).
- The observed lifetime for spallation products in the detector is approximately 36 msec, which is similar to what is expected for neutron capture on deuterium.
- The spatial, energy, and lifetime distributions indicate that the majority of the spallation events are consistent with a signal from the production of neutrons and their subsequent capture on deuterium. Future data will be analyzed to identify the longer-lived radioactive nuclei produced by the spallation of ^{16}O.

Closest Distance Between Spallation Candidate Fit Vertex and Muon Track Fit



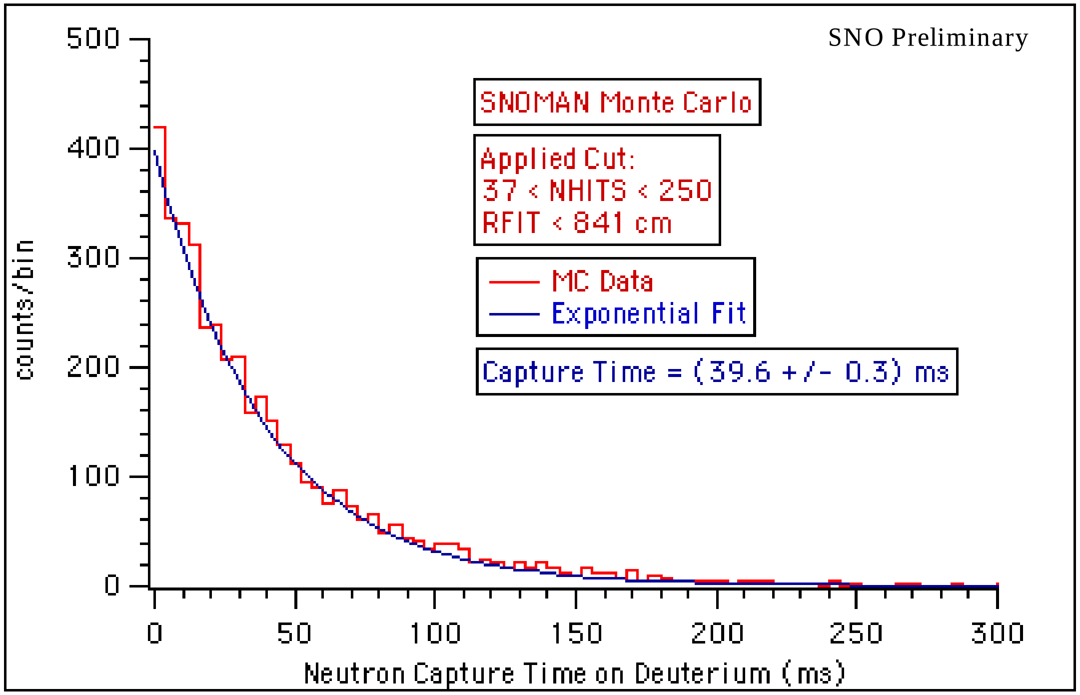
This plot shows the shortest distance between the fit vertex of the spallation candidates and the fitted muon track. The background curve comes from a control sample of events, several minutes after the muon, and it has been scaled down to reflect the contribution that we would expect in 1 second.

Fit Radius^3 of Spallation Candidates



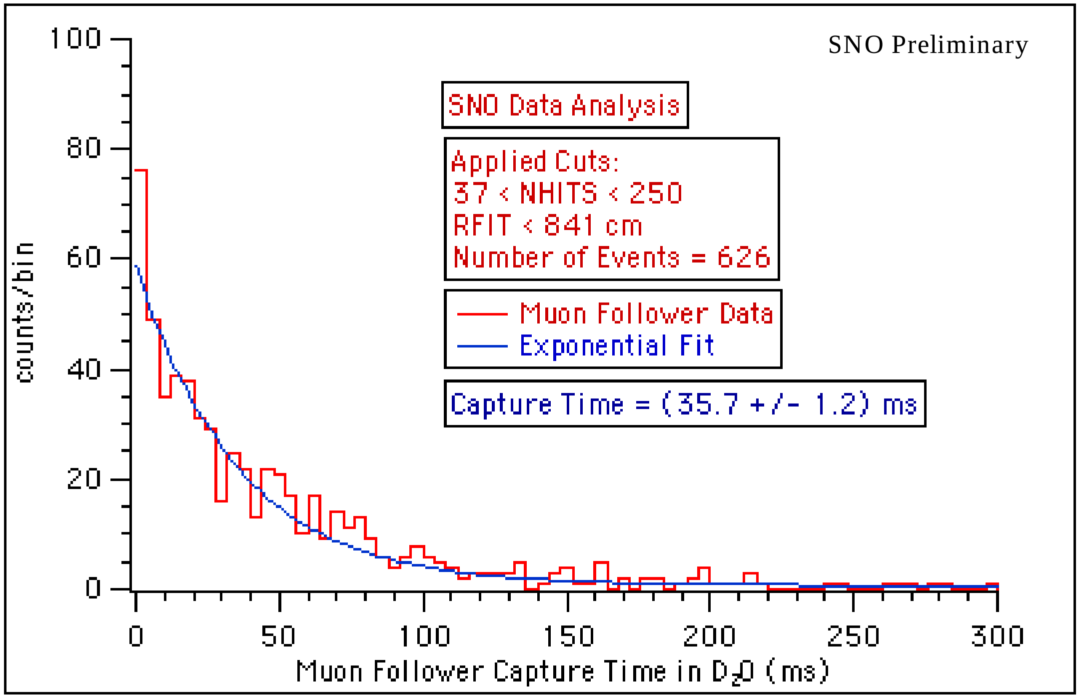
To illustrate that the spallation signal is largely confined to the heavy water region of the detector, the cube of the fit radius for the spallation candidates (in cm^3) is shown here. If the events are distributed uniformly in the detector, this distribution should be a flat line. The background curve comes from a control sample of events, several minutes after the muon, and it has been scaled down to reflect the contribution that we would expect in 1 second.

Monte Carlo Simulation of Neutron Capture in Heavy Water



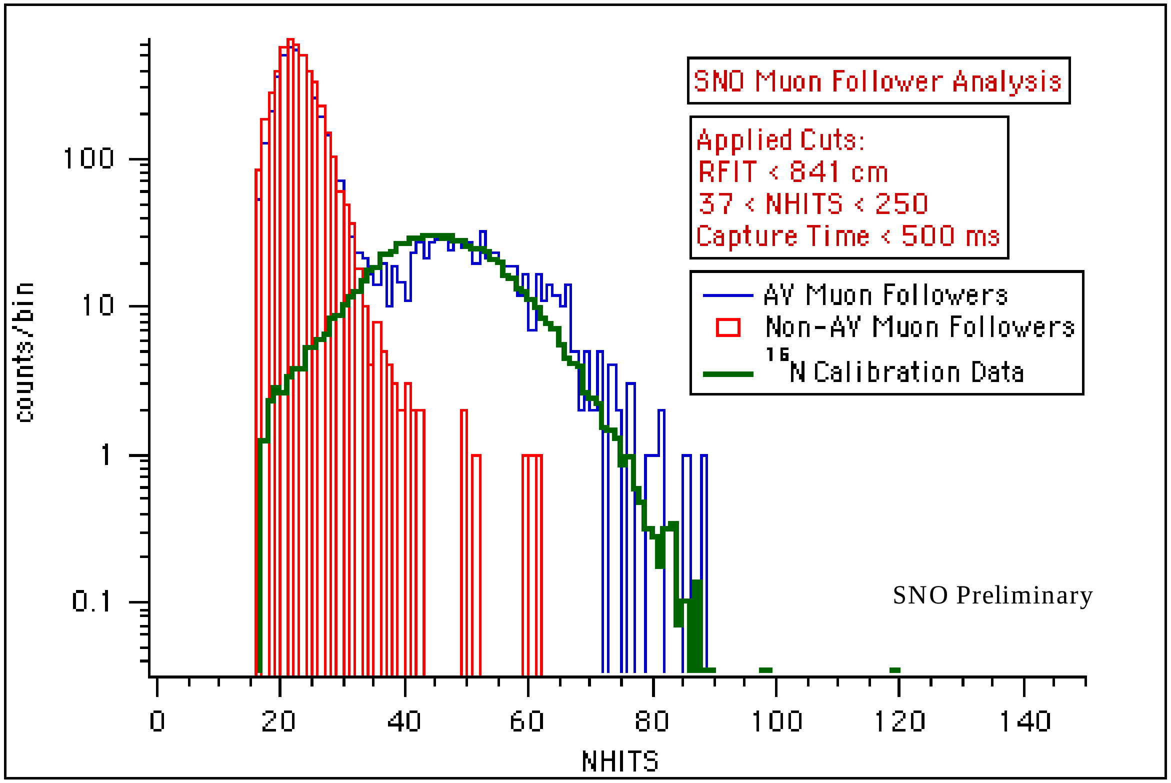
Once a neutron is produced in the detector, it rapidly thermalizes (~125 nsec) and walks randomly before capturing. A capture on ^{2}H produces a 6.25 MeV gamma ray. The plot above shows the time to capture from Monte Carlo simulations of neutrons, produced uniformly in the heavy water region. These simulations were performed using the SNOMAN software. The fit is to an exponential. Thus, this fit yields an approximate lifetime of 39.6 msec. On the average, the neutrons walk approximately 1.8 meters during this time.

Observed Lifetime of Spallation Candidates



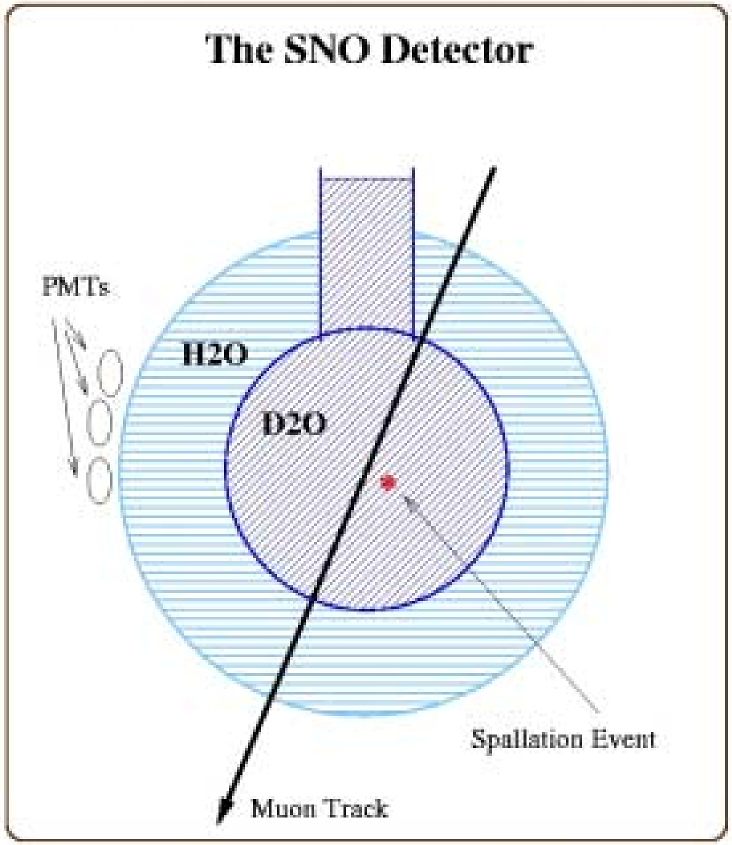
The time after a muon is shown here for events occurring in the 300 msec second period following a muon. These events must reconstruct inside the detector and have at least 37 but less than 250 phototube hits. This plot has been fit to an exponential, and a lifetime of 35.7±1.2 msec was obtained. The error here is statistical, however there are systematic differences in the geometry between the Monte Carlo and the data that have not been studied in terms of the lifetime.

Number of Phototube Hits for Spallation Candidates



Here the solid blue line represents the number of hit phototubes for spallation candidates in the 500 msec following a muon that traversed the heavy water. The red curve represents the same plot for spallation candidates following a muon that did not enter the heavy water. Notice that there is a bump, centered near nhits of 50 which is present only for the events following a muon that entered the heavy water. The green line shows the number of phototube hits for events from a run with the ^{16}N calibration source (6.13 MeV gamma).

Muon-Induced Spallation



The above drawing (not to scale!) depicts muon-induced spallation in the SNO detector.

In SNO, high-energy atmospheric muons travelling through the detector can break apart ^{16}O and ^{2}H nuclei in the heavy water region of the detector, producing free neutrons and radioactive nuclei.

The free neutrons are a background to the neutral current solar neutrino signal. In the absence of neutron detection enhancements, the most common capture is on ^{2}H, producing a 6.25 MeV gamma ray, which competes with the charged current and elastic scattering signals.

If radioactive nuclei decay by producing a high-energy beta or gamma ray, then these too can be detected. Thus, the betas and gammas from muon-induced spallation products are a background to the elastic scattering and charged current solar neutrino signals.

Therefore, it is important to understand the temporal and spatial correlations between the initial muon and the spallation events, so that these events may be rejected.