Supernova Relic Neutrino Studies at Super-Kamiokande

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***Abstract*. The diffuse supernova relic neutrino signal is of great cosmological interest but has not yet been observed. Currently inverse beta decay of anti-neutrinos in the Super-Kamiokande (SK, or Super-K) detector provides the world's best upper flux limit of 1.2 $\bar{\nu_e}$ events cm^{-2} s^{-1}, E$_{\bar{\nu}}$ > 19.3 MeV. A new method of tagging spallation products from cosmic ray muons, expanded fiducial volume, improved event reconstruction and selection as well as addition of new data will improve this limit and lower the energy threshold. These new methods as well as preliminary results using SK-I data are presented.**

***Keywords*: Supernova Relic Super-K**

I. Introduction

Core collapse supernovae emit enormous amounts of energy (approximately 10^{53} ergs), about 99% of which emerges as neutrinos. All the supernovae throughout history should together have created a diffuse supernova "relic" neutrino (SRN) background which we can search for on Earth. We have been looking for this signal at Super-Kamiokande (a 50 kton water Cherenkov detector located underground in Japan).

Of all supernova relic neutrinos, Super-K is mostly sensitive to electron type anti-neutrinos via inverse beta decay:

$$\bar{\nu_e} + p \rightarrow e^+ + n$$

Super-K then sees Cherenkov light emitted by the resultant positron, whose position and energy are reconstructed from the time and hit pattern of the Cherenkov light. The energy of the positron seen in Super-K is different from the energy of the original neutrino by 1.3 MeV, which is the mass difference of the proton and neutron. The Super-K convention is that energy means the total energy (visible and rest energy).

Previously (2003) a study was performed at Super-K using 1496 days of live data (the "SK-I" period) which did not see a relic signal. The analysis was limited to neutrino energies above 19.3 MeV due to strong backgrounds, most notably cosmic ray muon spallation. There are two irreducible backgrounds: $\bar{\nu}_e$ events from cosmic ray interactions in the atmosphere, and atmospheric ν_μ neutrinos that interact in the detector to create muons that are below Cherenkov threshold, which then decay into electrons. Both these backgrounds are indistinguishable from real SN relic events and must be modeled, then fit to the final data along with a possible relic component using a χ^2 method (see Fig. 1). The final result was a flux limit of 1.2 $\bar{\nu_e}$ cm^{-2} s^{-1}, E$_{\bar{\nu}}$ > 19.3 MeV [1]. We now seek to improve this result.

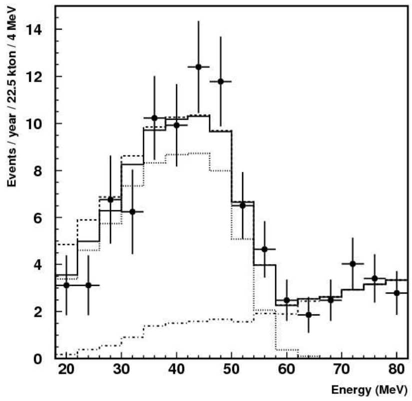

Fig. 1: Energy spectrum of SRN candidates from original study [1]. The dotted and dash-dot histograms are the fitted irreducible backgrounds from invisible muons and atmospheric ν_e respectively. The solid histogram is the sum of these two. The dashed line shows the sum of the total background and the 90% upper limit of the SRN signal.

II. Motivation

The SRN flux is related to parameters such as the rate of star formation, making it important to the cosmological community. Furthermore, recent studies [2], [3] predict that we are on the verge of discovery of the signal. One also puts an estimated lower bound on the rate (E_ν > 19.3 MeV) of 0.3 $\bar{\nu}_e$ cm^{-2} s^{-1}. Even if our current study does not see relic events, narrowing this allowed region may disallow some theories, as well as further constrain the stellar formation rate.

Furthermore, we have reason to believe a worthwhile improvement to our result is possible. Our dataset has increased in size (from 5 years to about 9 years), and we believe we can lower the analysis energy threshold as well as reduce inefficiencies with new analysis techniques.

III. Analysis Improvements

The SK data set includes many different types of events. To reduce the relic candidates to the irreducible backgrounds many cuts are necessary, including the following:

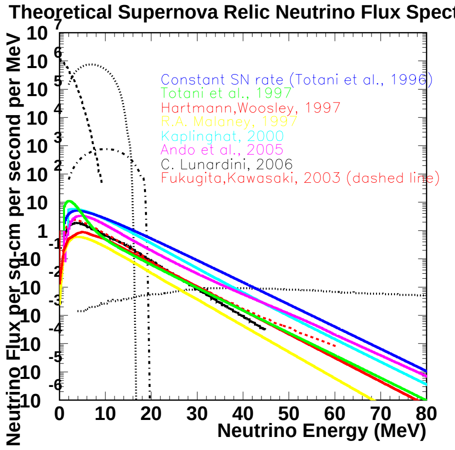

Fig. 2: Theoretical SRN Flux Spectra

A. *Spallation Cut*

Even under 2700 m.w.e. of rock, Super-K still sees approximately 2 Hz of cosmic ray muons entering the detector; these muons can interact with the oxygen, causing spallation. Spallation products are radioactive isotopes whose decay can mimic the SRN signal. These events are eliminated by spallation tagging, where SRN candidates are compared in position and time to preceding muons seen in the detector. Most spallation products have a short lifetime (on the order of 10 ms) but there are rarer, long lived products like $^{16}_{7}N$, which has a lifetime of 7.13 seconds. This cut is highly important for two reasons:

- It is a large source of inefficiency.
- The energy threshold for the analysis is limited by spallation background.

The second point is especially noteworthy, because SRN flux rises sharply as energy decreases (see Fig. 2). Thus, lowering the energy threshold of the analysis allows a significant increase in sensitivity, but can only be accomplished if spallation background is sufficiently reduced.

The spallation cut used in the original study was a combination of 2 separate cuts. The first is a three variable likelihood method developed for the Super-K solar analysis. The three variables are: the time difference from the relic candidate to preceding muon (t), the transverse distance from reconstructed relic candidate position in the detector to reconstructed muon track (l), and the "residual charge" (q), or difference of the total light intensity recorded by the detector for the event and that expected of a minumum ionizing muon. This cut was never tuned for the SN relic energy region, and does not use the best muon reconstruction tools available. The second cut simply rejects all events for 0.15 seconds after *every* muon. The combined inefficiency of the two cuts was 36%.

We are improving on this in a number of ways. First, we now fit the muons with one of our best muon reconstruction tools (Muboy). This not only increases reconstruction resolution, but Muboy also classifies the muon as one of four types:

- Muon that enters and leaves detector (single)
- Many muons enter at the same time (multiple)
- Muon that stops in the detector (stopper)
- Muon with short path in detector (corner clipper)

We then created a new spallation likelihood based on 4 variables and tuned them separately (at the appropriate energy) for each muon type. The four variables include time (t) and transverse distance (l) as before, but instead of residual charge (q), we found a new handle that allows us to predict where the spallation event occurs along the muon track.

This new handle emerges when we correlate every PMT to a section of the muon track. We can do this easily by noting that the muon travels at the speed of light in vacuum, while the emitted light travels at the speed of light in water. So, if t_1 is the time the muon enters the detector, t_2 is the time the PMT sees light, l_1 is the distance along the muon track before the light is emitted, l_2 is the distance the light travels before hitting the PMT, and c_{medium} is the speed of light in a particular medium, then we simply require that:

$$l_1 c_{vacuum} + l_2 c_{water} = t_2 - t_1$$

We further constrain by geometry, then add the recorded light intensity for the PMT to the resultant portion of the muon track in a binned histogram. This results in a profile of the light released along the track.

We find that many tracks with subsequent spallation have very strong peaks partway along this profile. We also find that the distance this peak lies along the track strongly correlates to where spallation products actually occur (see Fig. 3). Thus, our third spallation likelihood variable is the difference in where we expect a spallation event to lie along the track using this method, and where we really find the relic candidate compared to the muon track in the data. Our fourth variable is the total charge released from a 5 meter section of muon track centered on the peak of our profile histogram, akin to the residual charge used before.

These new methods have allowed us to greatly reduce inefficency in the previously allowed energy region ($>$ 19.3 MeV) from 36% to 16%. Also, it has allowed us to lower the energy threshold by 2 MeV. In this new region we use a tighter constraint, with an inefficiency of 20%.

This new method of predicting spallation position along the muon track is a very interesting result that may be useful to other experiments seeking to tag spallation. Although we do not fully understand the physics involved, the correlation in the data is undeniable.

B. *OD correlated cut*

Super-K has an outer detector (OD) as well as the main inner detector (ID). When enough light is seen by

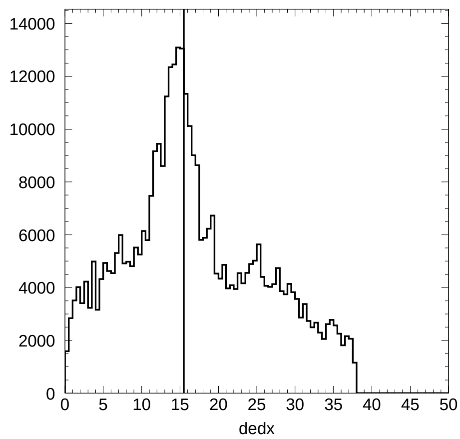

Fig. 3: Muon track light emission profile. The vertical line represents where the the spallation product actually occured in this case.

OD PMTs, the OD electronics will trigger. All events where the OD electronics triggers are eliminated from the sample, as neutrino events must be fully contained. However, the OD PMT coverage is a factor of 6 less than that of the ID, and sometimes a lower energy event from outside can slip into the detector without triggering the OD electronics. Nevertheless, some OD tubes are usually hit for an incoming event, even if it was not enough tubes to cause a trigger. Thus, position and timing correlation between ID and OD hit tubes were studied in order to manufacture a more stringent cut. If there are hit OD tubes closely correlated in both position and time to the hit ID tubes, it is likely that the event came in from outside the detector, and the event is rejected.

C. *Expanded fiducial volume*

The original analysis rejected all events within 2 meters from the ID wall, leaving 22.5 ktons of fiducial volume. This is the cut used in the Super-K solar analysis, and was never optimized for a supernova relic study. Events near the wall are a problem because radioactivity from outside the detector leak in here (for example, radioactive radon in the surrounding rock, or radioactive elements in the PMT glass itself). Also it is more difficult to reconstruct the energy of events near the ID wall. When an event is near the wall, if it travels in a direction towards the wall, the Cherenkov cone will shine all of its light onto relatively few PMTs, thus appearing less energetic then it really is to the reconstruction software.

To address the issue of energy reconstruction, a correction factor was created to modify the energy scale. This energy correction factor was developed utilizing monte carlo studies, and is a function of the distance the relic candidate lies from the wall, along the candidate's reconstructed direction. It simply scales up the original reconstructed energy to correct for being near the wall.

To address the problem of radioactivity leaking into the detector from outside, we made improvements to an already existing cut, which uses a similar parameter as the energy correction. Instead of the distance along the event direction to the wall, we use the distance to the wall traveling opposite the event direction. This represents the distance an event would have had to travel in the detector if it originated from the wall (or just outside). The larger this distance, the less likely it is that the event could be such a background. This cut is energy dependent, as many more of these radioactive events start occuring as the reconstructed energy drops below 18 MeV.

Combined, these two improvements have allowed us to expand the fiducial volume from 200 cm to 50 cm from the wall for events with reconstructed energy > 18 MeV (E_ν > 19.3 MeV), although the 200 cm fiducial volume is still currently used for the new region (17.3 MeV < E_ν < 19.3 MeV).

D. *Pion likelihood cut*

Sometimes atmospheric neutrinos can interact to create pions, which also make Cherenkov light. Unfortunately, many of these slip through our other cuts, and charged pions can be a background for our analysis. Electron events tend to undergo multiple Coulomb scattering much more then pions, which have a greater mass and live too briefly to travel far. Thus Cherenkov rings due to electron events appear fuzzy, while pion events cause rings that are sharp. A likelihood was constructed to measure the "sharpness" of the Cherenkov ring, which is then used to eliminate pion events from our sample.

E. *Multiple ring cut*

Sometimes atmospheric neutrinos can interact in the detector and create electrons and pions simultaneously. Two distinct rings will be created, but often only one peak will be seen in the timing. To find these events we implement a ring counting method using Hough transformations. If more then one ring is found, the event is rejected.

F. *Other cuts*

Other important cuts in the analysis worth mentioning include:

- A solar angle cut on reconstructed events below 21 MeV E_ν to eliminate solar neutrino events.
- A cut on events with more then one timing peak within the 1.3 μs event window. This can happen, for instance, when a sub-Cherenkov muon stops in the detector and decays very quickly.
- A cut on the reconstructed opening angle of the events. Real events will reconstruct near the electron opening angle of 42 degrees, while many backgrounds do not. Most notably this helps eliminate low energy muons (which have a different opening angle due to their greater mass), and multiple gamma events, which tend to reconstruct with a

large opening angle due to their more isotropic nature.

IV. Conclusion

We are currently reprocessing the data used in the original study with our new techniques, after which a χ^2 method similar to that used in the original study will be utilized to extract our new SK-I limit. Next we will reprocess the subsequent two years of data (SK-II), which had reduced PMT coverage (19% instead of 40%). Because of this difference, we may have to retune our cuts for this data. Lastly we will process two more years of data (SK-III), which also has 40% cathode coverage. Lastly these results will be combined into a single final limit. Unfortunately this is not yet complete as of the time of this writing, and therefore cannot be included. However the result from SK-I data should be complete very soon (July 2009).

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