Neutrinos from the Sun

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Abstract. The theory of solar neutrino generation is reviewed with an emphasis on the measureable fluxes from the ^{8}B , ^{7}Be , and $p-p$ reactions. The "solar neutrino problem" is summarized. It is emphasized that the solar neutrino problem is not just a problem with solar model predictions, but that there is considerable difficulty in making a quantitatively consistent picture of the relative rates of the different reactions from current experimental data. In addition, recent results from Super-Kamiokande are presented for 825 days of operation. The measured absolute flux, spectrum, and day/night asymmetry of ^{8}B solar neutrino-induced recoil electrons are given. Based on these results, some regions of neutrino oscillation parameter space are ruled out.

INTRODUCTION

Our sun is a typical main sequence G2 star undergoing core hydrogen burning with a central temperature determined essentially by its (1) *mass*, (2) luminosity , and (3) radiative opacity . Since the mass and luminosity are well-known, it is only the radiative opacity that gives significant uncertainty as to the core temperature and hence the relative nuclear reaction rates occuring there. The radiative opacity depends on such things as the metalicity, mixing, He abundance, density, and pressure inside the sun. Solar neutrinos provide direct information on relative reaction rates, and hence on conditions in the core of our sun.

Using measured and/or calculated cross-sections and a model of solar mass distribution and chemical composition the expected flux of neutrinos from various nuclear processes has been calculated, and for the last twenty-five years measurements have been carried out to test these predictions. All experiments to date have found too few neutrinos compared to most calculations [1–4]. This is the famous *Solar Neutrino Problem.*

TABLE 1. The $p-p$ reaction chain.

reaction	(%)	ν energy (MeV)
$p+p \rightarrow {}^2H + e^+ + \nu_e$	100.	< 0.420
${}^2H + p \rightarrow {}^3He + \gamma$	100.	
${}^3He + {}^3He \rightarrow {}^4He + p + p$	85.	

THE SOLAR NEUTRINO PROBLEM(S)

To solve the solar neutrino problem many people have speculated that perhaps our model of nuclear reactions taking place in the sun is wrong. When analyzed coherently, however, the it can be seen that the data are inconsistent with virtually *all* current solar models, so our models would have to be wrong at a very fundamental level. This can be illustrated by considering the contributuions of the three basic neutrino-producing chains in most models: (1) $p-p$, (2) ${}^7Be$ -${}^8B$, and (3) CNO.

A The $p-p$ Reactions

Table 1 shows the $p-p$ solar reaction chain according to a “generic” standard solar model of Bahcall, Basu, and Pinsonneault [5]. The so-called “pep” and “Hep” reactions have not been included, since their flux is far too low to significantly affect the interpretation the absolute flux measurements of current experiments.

If one assumes that solar energy production is mostly due to this basic reaction chain, then the number of $p-p$ neutrinos at Earth is relatively easy to calculate. Unless one postulates an alternative energy source for the sun that does not involve changing hydrogen to deuterium by this, the most simplest of all the solar reactions, the $p-p$ neutrino flux is essentially fixed.

B The Beryllium-Boron Reactions

The ${}^8B$ and ${}^7Be$ chains are, of course, more complicated. Table 2 shows the relevant reactions. The production rate of ${}^7Be$ depends on the details of the mixing of ${}^3He$ with ${}^4He$. The amount of mixing, and the temperature in the mixing region determine the ratio of this side reaction to the main $p-p$ chain. In the BP98 model it is 15%.

Having manufactured some ${}^7Be$, then there are two major possibilities as to its fate. One possibility is that the ${}^7Be$ will electron capture from a K or L state to form ${}^7Li$, resulting in two neutrino lines at 861 and 383 keV. Another possibility,

TABLE 2. The Be-B reaction chain.

reaction	(%)	ν energy (MeV)
$^3He + {}^4He \rightarrow {}^7Be + \gamma$	15.	
$^7Be + e^- \rightarrow {}^7Li + \nu_e$	15.	0.861,0.383
$^7Be + p \rightarrow {}^8B + \gamma$	0.02	
$^8B \rightarrow {}^8Be^* + \nu_e$	0.02	< 15
$^8Be^* \rightarrow 2\alpha$	0.02	

although a rare one, is that the ^7Be will capture a proton to become ^8B . In the BP98 model this happens to only 0.13% of the ^7Be nuclei. The rate of ^8B formation is obviously determined by the temperature in the ^7Be region (a high temperature is needed to overcome the Coulomb barrier) and by the form factor S_{17} for the proton capture reaction. This form factor appears in the parametrization

$$\sigma_{^7Be+p\rightarrow {}^8B+\gamma} = S_{17}(E)e^{-2\pi\eta(E)}/E_{cm} \tag{1}$$

where $\eta(E) = Z_1(=1)Z_2(=7)e^2/v$, v being the relative velocity between the $^7Be$and proton. A few years ago S_{17} was a major source of uncertainty in the ^8Bflux calculation, but it has now been measured with some confidence by Hammache, *et al.* [6]. recent work by Adelberger, *et al.* [7] have combined these recent results with older ones to deduce a value of

$$S_{17}(0) = 19^{+8}_{-4}\, eV \cdot b \tag{2}$$

In addition to the S_{17} uncertainty, there is also the problem of the solar radiative opacities. An increase in the opacity naturally raises the core temperature, increasing the production of ^8B . For example, such an increase would occur if there is significant mixing of ^4He and other $Z > 2$ elements into the core region. One type of mixing is the gravitational "settling" of these materials. Other proposed methods involve convection currents of various sorts. As an example of the effect of such mixing, the inclusion of gravitational settling into the model of Bahcall and Pinsonneault changed the results of their ^8B neutrino flux calculation by 23% from the BP92 model to the BP95 model. Coincidentally, this 23% change was reduced to 7% by incorperating the new S_{17} measurements.

C The Measurements

Table 3 shows the results of the solar neutrino experiments that have been performed. The Kamiokande experiment [2] and Super-Kamiokande experiment [8] are primarily sensitive to ^8B neutrinos and so there is significant uncertainty (14%) in the predicted absolute flux. The SAGE [3] and GALLEX [4] experiments, however are primarily sensitive to the $p - p$ reaction, so the uncertainty is much smaller

TABLE 3. Current solar neutrino measurements and comparison with the BP98 solar model.

experiment	BP98 prediction	measured
chlorine	(SNU)	
	5.9 ^{8}B	
	1.1 ^{7}Be	
	0.7 other	
	$7.7^{+1.2}_{1.0}$ total	
Homestake		2.54 ± 0.20
water	$(\times 10^{6} cm^{-2} s^{-1})$	
	$5.15^{+0.98}_{-0.72}$ ^{8}B	
Kamiokande		$2.80 \pm 0.19 \pm 0.33$
Super-Kamioande		$2.45 \pm 0.04 \pm 0.07$
gallium	(SNU)	
	69.6 $p-p$	
	34.4 ^{7}Be	
	12.4 ^{8}B	
	12.6 other	
	129^{+8}_{-6} total	
Sage		67 ± 8
Gallex		78 ± 6

(5%). All these experiments are significantly below predictions, regardless of experimental technique.

In addition to the low measured flux values, there is an inconsistency between the experiments themselves. Since the Super-Kamiokande experiment measures essentially a pure ^{8}B flux, then this flux can be extrapolated to a prediction of 5.9 SNU (down from 12.4 SNU) for the SAGE and GALLEX experiments. Adding the $p-p$ and ^{8}B fluxes together gives $69.6 + 5.9 = 75.5$ SNU. This is almost equal to the measured values. Of course, since the ^{8}B neutrinos *come* from ^{7}Be, then there is no room left for the requisite flux of these neutrinos. This is sometimes called the "New" Solar Neutrino Problem because it does not depend explicitly on the details of the solar model.

D What About CNO?

The CNO cycle uses carbon, nitrogen, and oxygen as catalysts to convert protons to ^{4}He. Since the Coulomb barriers are even higher than the $p-p$ cycle, the required temperatures for this to proceed are significantly above that of the $p-p$ reactions. Thus only about $2 \pm 1\%$ of the sun's energy output is expected to come from the CNO cycle. To increase this fraction would require a significantly higher core temperature in the sun than is predicted - which would result in a very large increase in the production of ^8B. Since the CNO rate in our sun is dominated by the reaction $^{14}N + p \rightarrow ^{15} O + \gamma$, which has been measured down to as low as 100 keV [], it can be shown that if we wish to increase the amount of the CNO contribution to displace $p-p$ by 50% (to explain the measurements), then we would have to increase solar temperature by roughly 15%. This would actually *increase* the ^8B production dramatically, about a factor of six. This is far outside current experimental and theoretical uncertainties, so CNO competition with $p-p$ is not a viable solution to the solar neutrino problem.

I NEUTRINO OSCILLATIONS

Neutrino oscillations are a possible solution to the low measured rates of solar neutrinos. Such flavor mixing of neutrinos could produce one or more "smoking guns" that would be measureable by a new generation of experiments. These might take the form of (1) spectral distortions, (2) a day/night asymmetry, or (3) a seasonal variation beyond the $\frac{1}{r^2}$ effect of the Earth's orbital ellipicity.

A simple picture is to imagine that solar ν_e's are mixed with another neutrino flavor such that the wavefunction acquires a significant component of this second flavor as it propagates from the Sun to the Earth. This magnitude of the second component depends on the mixing angle (θ) between the two eigenstates and also the phase difference between the components induced by the difference of the mass of the components ($\delta m^2 = m_2^2 - m_1^2$). Many studies have been done to constrain possible values of these mass and mixing parameters using the absolute values of the measured fluxes compared to the predicted values. Figures 1 and 2 show the two regions of the parameter space that are consistent with the measured values in table 3. These regions have acquired their own names: (1) Small Mixing Angle (SMA), (2) Large Mxing Angle, and (3) Just-So (or Vacuum).

The SMA solution is characterized by the so-called "MSW Bathtub" named for the bathtub-shaped spectral distortion seen from the Mikhayev-Smirnov-Wolfenstein [9] matter oscillations in the sun. In this scenario, the ν_e convert to the second neutrino flavor by a resonance effect occuring in the solar interior between the natural oscillation length and the effective mass caused by the fact that the ν_e can interact via CC with solar electrons whereas other flavors cannot. This allows for almost full conversion from one neutrino type to the other even though the mixing angle is small. Such a distortion would naturally lead to distortions in the recoil electron spectrum from the $\nu_e + e^- \rightarrow \nu_e + e^-$ reaction measured by Super-Kamiokande. Note that since the spectrum of ^8B neutrinos depends only on the physics of beta decay and not upon the solar model. Observation of a distortion would be one "smoking gun."

A smoking gun for the LMA solution would be the observation of the regeneration of ν_e from a well-mixed beam via interaction with electrons in the Earth. In this case, the beam would be mixed before it arrived at Earth due to the fact that the oscillation length is small compared to the solar radius. The regeneration would occur as the beam passed through the Earth (i.e., when the sun was below the horizon - a condition which neutrino physicists refer to as "Night"). In this case, spectral distortions would be smaller than for the SMA solution. This Day/Night asymmetry is also solar model independent.

For the Just-So case, the number of oscillation lengths between the Earth and Sun is small, so that possible smoking guns might be a radical spectral distortion that is seasonally dependent due to the changing Earth-Sun distance over the course of the year. Again, there is little dependence on the specific solar model.

II THE SUPER-KAMIOKANDE MEASUREMENTS

Super-Kamiokande is an underground, 32-kton fiducial volume, water cherenkov detector located in the Kamioka Mine in central Japan. About 40% of the surface

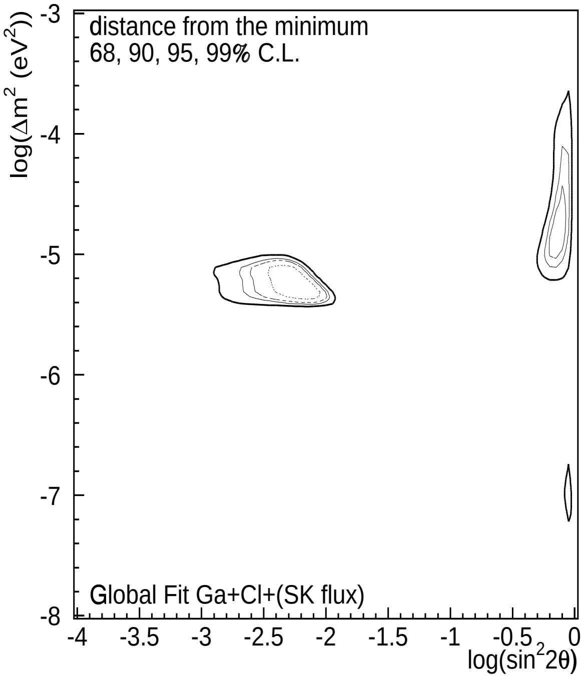

FIGURE 1. The regions of neutrino mass and mixing parameter space allowed by comparison of the measured solar neutrino fluxes with the predictions from the BP98 solar model. The region to the top left is called the Small Mixing Angle (SMA) region, and the region to the right is called the Large Mixing Angle (LMA) region.

of the cylindrical tank is covered with photocathode, which results in about 6.5 photoelectrons/MeV of deposited energy. The detector records charged particle tracks with efficiency better than 90% for electron energies down to 5.2 MeV (it is even lower now due to recent improvements). Although the detector triggers at over 100 Hz, a 2.5 meter veto system and fiducial volume vertex cut of 2 meters from the PMT planes reduces this to 0.14 Hz. Making a time-distance cut around cosmic ray muons passing through the detector reduces this further to about 100/hour. A final cut on entering events near the edge of the fiducial volume results in a final data rate of about 10 events/hour. Figure 3 shows the distribution of the cosine of the angle between the fitted event directions and the solar direction for events with energy above 6.5 MeV. The solar peak is clearly seen and corresponds to a measured flux of *all* ^8B neutrinos of

$$2.45 \pm 0.04(stat.) \pm 0.07(syst.) \times 10^6 cm^{-2} s^{-1} \tag{3}$$

or a ratio of data to prediction of

$$\frac{Data}{BP98} = 0.475^{+0.008}_{-0.007}(stat.) \pm 0.013(syst.) \tag{4}$$

At the present time there is a separate reduction chain for events less than 6.5 MeV (although we are working on a unified analysis) and so figure 4 shows the

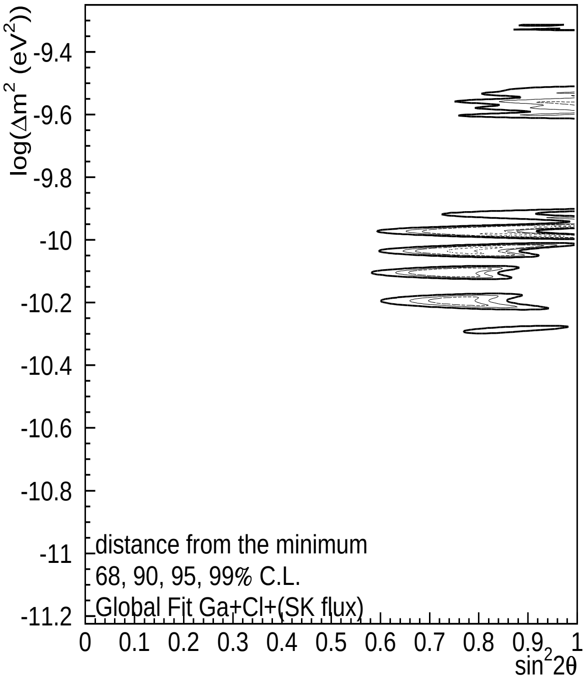

FIGURE 2. The regions of neutrino mass and mixing parameter space allowed by comparison of the measured solar neutrino fluxes with the predictions from the BP98 solar model. This shows the allowed regions of the Just-So (or Vacuum) oscillation region.

same angular distributions for events 5.0-6.5 MeV. Due to the large background in the 5.0-5.5 MeV and the changing trigger efficiency we do not yet use these data in the analysis that follows.

A The Recoil Electron Spectrum

A plot similar to figure 3 can be made for each bin of total electron energy in order to make a spectral plot of recoil electron energy. We can now divide each bin by the BP98 solar model prediction to produce the flattened spectrum shown in figure 5. A signal for neutrino oscillations would be a deviation from flat for this spectrum. A χ^2 fit to flat gives a confidence level of 11.2%, which is not significant enough to be considered a "smoking gun."

There may be a small upturn at the end of the spectrum, but this may be due to a larger-than-expected enhancement of high-energy neutrinos from the supposedly rare HeP reaction, $^3He + p \rightarrow ^4 He + e^+ + \nu_e$. This has a Q-value of 18.77 MeV and large uncertainty in the rate. Making the normalization for this flux a free parameter results in the curve shown in figure 5 for the spectrum. This gives a confidence level of 24.4% for flat, with a best-fit HeP contribution of 16 times

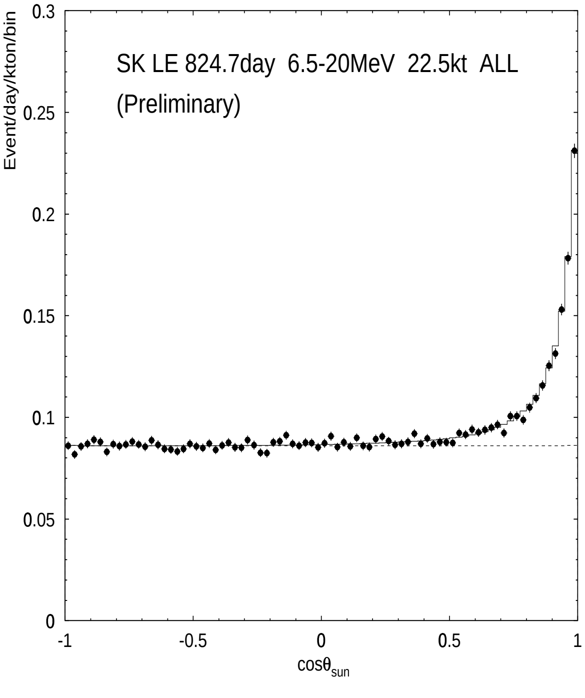

FIGURE 3. The cosine of the angle between the fitted event directions and the solar direction for events with total electron energy greater than 6.5 MeV for 825 days of Super-Kamiokande operation.

the BP98 prediction. Thus no significant spectral deviation is seen in the 825-day sample.

B Day/Night Asymmetry

Figure 6 shows the data above 6.5 MeV divided into 10 equal bins of the cosine of the solar zenith angle. Bin N5 roughly corresponds to the Earth's core and might have a enhancement under some SMA scenarios. No significant enhancement is seen. There is a slight asymmetry between total Night flux and Day flux, however. Defining a Day/Night asymmetry parameter then

$$\frac{(D-N)}{\frac{1}{2}(D+N)} = -0.065 \pm 0.031(stat.) \pm 0.013(syst.) \tag{5}$$

Such an overall enhancement of the night flux is expected in some LMA scenarios.

The systematics in this case are determined from studies of the spallation products from cosmic ray muons. These spallation products are in the same energy range as the solar neutrinos and should be uncorrelated with the sun. Small asymmetries seen in these data may be due to residual asymmetries in detector response

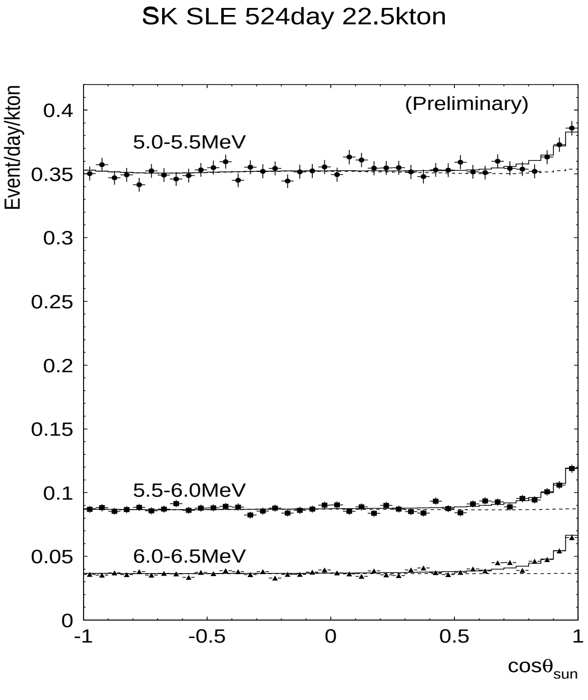

FIGURE 4. The cosine of the angle between the fitted event directions and the solar direction for events with total electron energy less than 6.5 MeV for 524 days of Super-Kamiokande operation.

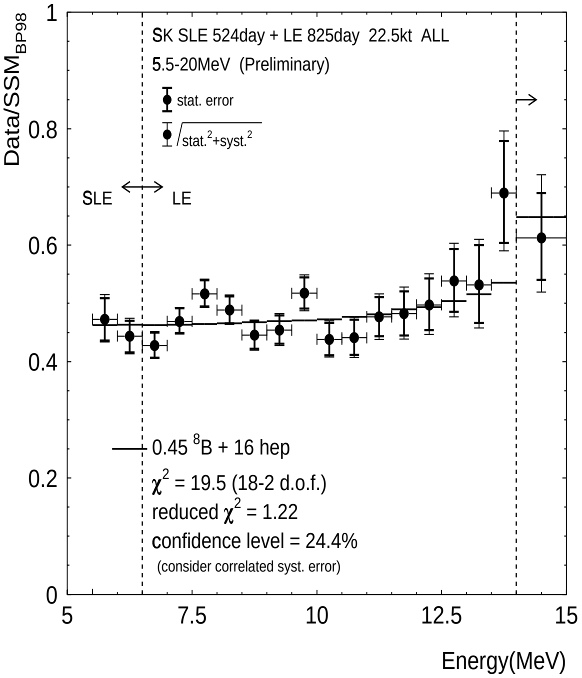

FIGURE 5. Data/BP98 for 825 days of Super-Kamiokande operation. The solid curve shows the expectation from treating the possible contribution from HeP neutrinos as a free parameter.

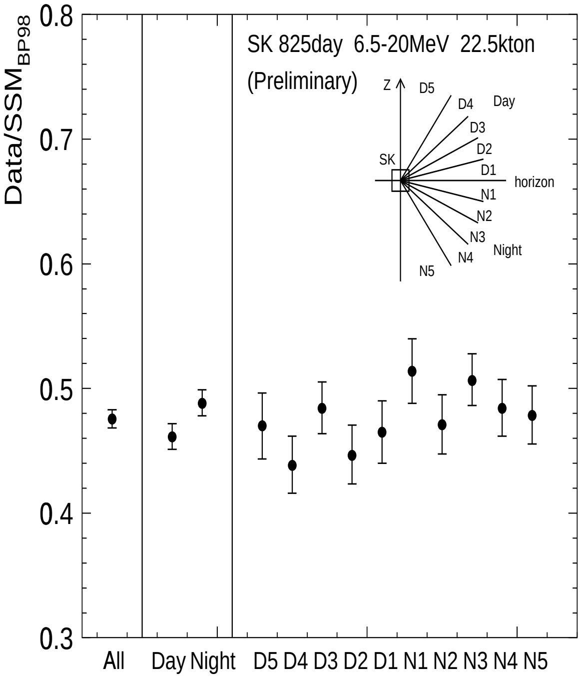

FIGURE 6. Data/BP98 divided into bins of Day and Night.

over time or angle, and are small compared to the statistical uncertainties. Several more years of running are clearly necessary to resolve whether this 2σ deviation is real or not.

C Seasonal Variation

Figure 7 shows the variation of the measured solar neutrino event rate as a function of time since detector turn-on in April, 1996. The curved line shows the variation expected from the Earth's elliptical orbit. No significant deviation is seen over the 3 years of operation.

D Limits on Oscillations

Using the measured spectrum and Day/Night asymmetry then limits can be placed on oscillation parameters using a standard χ^2 test. Assuming that the HeP neutrino flux has a free parameter normalization, then figure 8 shows the exclusion region in the MSW region for 68, 90, 95, and 99% confidence levels. The inner dark line is the 99% confidence level exclusion region. There are two best fit points with

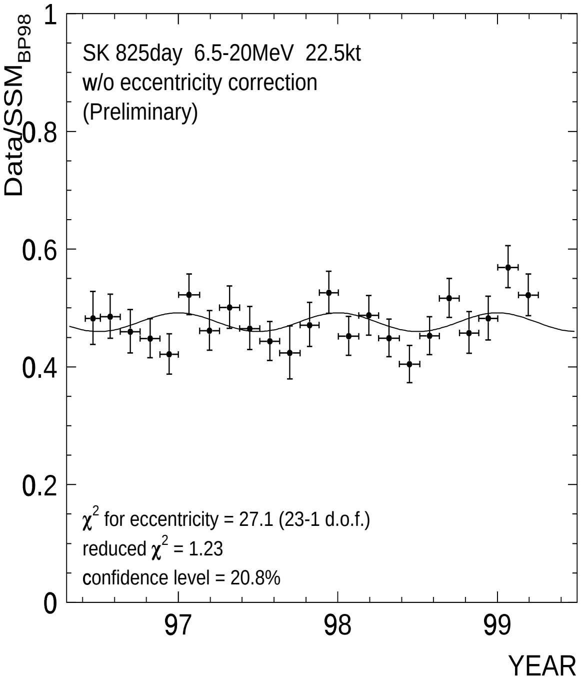

FIGURE 7. The cosine of the angle between the fitted event directions and the solar direction for events with total electron energy less than 6.5 MeV for 524 days of Super-Kamiokande operation.

roughly equal probability, at (0.,-6.6) with 16.3% and at (0.,-4.6) with 15.8%. It should be emphasized that this exclusion region does *not* include the constraint of the absolute flux. These probabilities are only slightly better than the no-oscillation hypothesis, which gives 7.9%.

A significant portion of the SMA solution is excluded at the 99% confidence level by these measurements, although not all. It should be noted that these results are still statistically limited, despite the huge size of Super-Kamiokande and so further improvements in sensitivity are to be expected.

In the Just-So region, figure 9 shows the excluded region. Essentially *all* of the allowed regions from the comparision with absolute flux are excluded. Of course, it may be in the future that changes to the ^8B flux can move the allowed regions in the Just-So region significantly.

III CONCLUSIONS

No significant spectral deviations are seen in the recoil electron spectrum from ^8B solar neutrinos in Super-Kamiokande from 825 live days of operation. A small Day/Night asymmetry is seen, but it is not statistically significant. Based on these

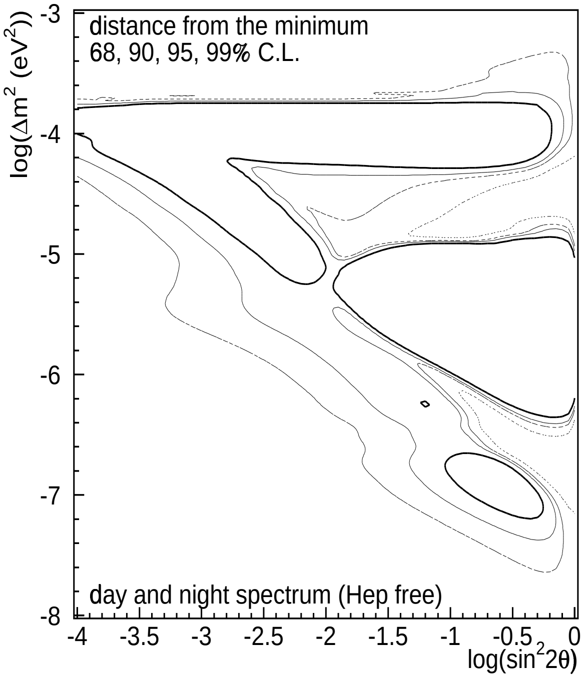

FIGURE 8. Excluded regions of oscillation parameter space based on the recoil electron spectrum and Day/Night asymmetry measurements only.

observations, the SMA oscillation solution is disfavored over the LMA solution in terms of excluded parameter space, but is is not yet ruled out. Just-So oscillations no longer can fit both the absolute flux constraints and the spectral data to better than a 1% confidence level. It is expected that continued running of Super-Kamiokande along with data from the Sudbury, Borexino, and KamLAND experiments have a good chance of determining if solar neutrinos are oscillating or not.

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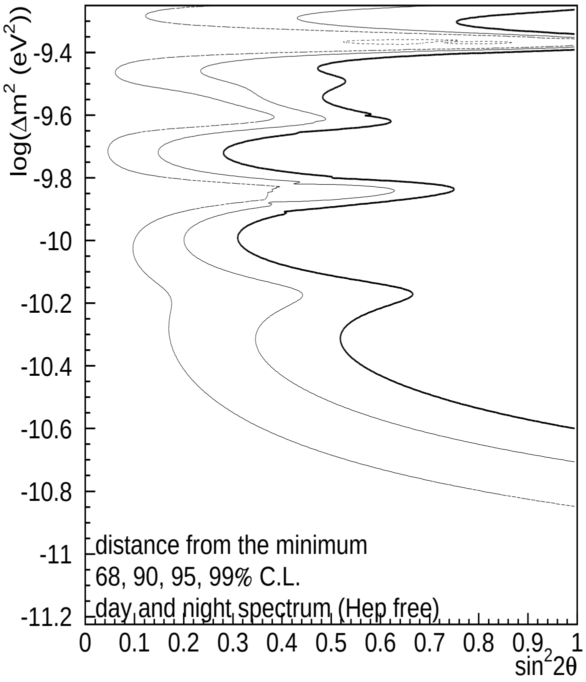

FIGURE 9. Excluded regions of oscillation parameter space based on the recoil electron spectrum and Day/Night asymmetry measurements only.