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SOLAR NEUTRINO RESULTS FROM SUPER-KAMIOKANDE

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ABSTRACT

The new neutrino observatory, Super-Kamiokande, is located near Kamioka, Japan and has been collecting data since April 1996. Super-Kamiokande is a 50,000 m^3 water-Čerenkov detector. Forty percent of the surface area on the walls of the 32,500 m^3 inner detector is covered by many photomultiplier tubes. With the current trigger threshold of about 5.5 MeV, the detector is sensitive to only the ^{8}B neutrinos from the Sun. The preliminary total neutrino flux measurement above a 7 MeV energy threshold is $2.70\ ^{+0.09}_{-0.08}$ (stat) $^{+0.15}_{-0.10}$ (syst) $\times 10^6\ \frac{\nu}{\mathrm{cm^2 s}}$. When the measurement is compared with the most recent Standard Solar Model flux prediction (BP95) (Bahcall and Pinsonneault, 1995), the preliminary ratio of data/SSM is $0.408\ ^{+0.013}_{-0.012}$ (stat) $^{+0.023}_{-0.014}$ (syst). The preliminary measured fluxes during day and night yield a fractional difference of $+0.004 \pm 0.033$ (stat) $\pm\ 0.017$ (syst).

THE SUPER-KAMIOKANDE DETECTOR

Super-Kamiokande (Conner, 1995) is a water-Čerenkov detector built to study a variety of physics topics, especially the Solar Neutrino Problem. The exterior of Super-Kamiokande is a stainless steel tank 41 m tall and 39 m in diameter which holds 50,000 m^3 of ultra pure water. This volume is divided into two optically separate detectors, inner and outer. The inner detector contains 32,500 m^3 of water (22,500 m^3 of which are used for the solar neutrino measurement) viewed by 11,146 photomultiplier tubes (PMTs) 50 cm in diameter. The 1 pe timing resolution of these large PMTs is 2.8 ns. The outer detector forms a cylindrical shell surrounding the inner volume and is used to differentiate between events with entering, exiting, and contained particles. This 2.5 m thick veto shield is instrumented with 1,885 PMTs and accompanying waveshifter plates to increase the total light collection area. The outer PMTs are 20 cm in diameter and face towards the outer wall of the Super-Kamiokande tank. Both walls defining the outer detector are lined with a reflective material to enhance the overall light collection efficiency of the outer PMTs. The detector is located in a lead and zinc mine near Kamioka, Japan at a depth of 2800 mwe.

Since Super-Kamiokande is situated underneath a mountain, the rate of cosmic-ray muons triggering the detector is reduced to $\sim$2.2 Hz. The remainder of the 10-12 Hz of triggers from Super-Kamiokande are low energy events. The current trigger threshold (defined as the energy where the trigger is 50% efficient) is $\sim$5.5 MeV. The majority of the low energy triggers are background for the solar neutrino analysis. Using our overall efficiency for the detector and the analysis, a solar neutrino event rate of 35.9 (41.8) events/day above 7 MeV is predicted by the BP92 (BP95) Standard Solar Model (Bahcall and Pinsonneault, 1992 and Bahcall and Pinsonneault, 1995).

Because of this high solar neutrino event rate, the significance of the measurements made by Super-Kamiokande will ultimately be limited by systematic uncertainties, not statistical errors. For this reason, two groups within the Super-Kamiokande collaboration each perform completely independent solar neutrino analyses. All data filtering, event reconstruction, and cut selections are done separately. The only overlap between the two groups is the use of the raw data and the data from various calibration sources. One of the analyses will be briefly described here (Conner, 1997). Results from both groups will be compared and the “official” Super-Kamiokande solar neutrino results will be given.

SOLAR NEUTRINO EXTRACTION

A multi-stage filter is run on the ~1 million events/day to find the ~1000 events/day which are solar neutrino candidates. The first stage performs a track fit on the single through-going muon events and runs a fast vertex fitter (~1.2 m resolution) on every low energy event. The best fit track parameters are saved for the muon events so low energy spallation events may be identified and the PMT data can be removed from the data file (almost factor of 2 reduction in data size). The low energy trigger rate is dominated by low energy background near the walls of the inner detector. A loose fiducial volume cut (27,000 m^3) is made by only saving the low energy events whose vertices are further than 1 meter from the inner detector edge (removes 2 of every 3 low energy events).

The second stage in the filter process selects good data runs, performs a track fit on the stopping and multiple muon events, more precisely fits the vertex (~70 cm resolution) and direction of all remaining low energy events, and removes "junk" events from the data set. The final fiducial volume cut of 22,500 m^3 is made based on the precise vertex location. The output of this step includes the PMT data for good candidate solar neutrino events and the track fit parameters for all muon events.

The third step in filtering is the application of final cuts to further reduce the background. First, all events below a particular energy threshold are cut from the data sample. Spallation events are identified by a time and positional correlation between the low energy event and a previous muon. All potential spallation events are cut (background reduced to $\frac{1}{4}$th) and the reduction in total detector exposure (Active Volume × Live Time) is calculated. A cut is made on the quality of the vertex fit.

PRELIMINARY RESULTS

Using the final event sample, correlations with the Sun location are examined. Figure 1 shows the distribution of the cosine of the angle between the low energy event direction and the direction from the Sun. Events coming directly from the Sun would have $\cos\theta_{\text{sun}} = 1$. A clear excess above background is seen for event directions pointing from the Sun. Also shown in Figure 1 is a curve representing the expected signal above the fit background predicted from the BP95 Standard Solar Model flux (Bahcall and Pinsonneault, 1995).

The background level is fit over the range $-1 \leq \cos\theta_{\text{sun}} < 0.5$. The expected shape of the solar neutrino signal is known from analyzing simulated solar neutrino events. The best fit normalization to Signal + Background yields the number of solar neutrino events in the data sample. The number and rate of excess events near the Sun is given in Table 1 for several different energy thresholds. The rate of events which should be in our final data sample as predicted by two different Standard Solar Models (Bahcall and Pinsonneault, 1992 and Bahcall and Pinsonneault, 1995) is also given in Table 1.

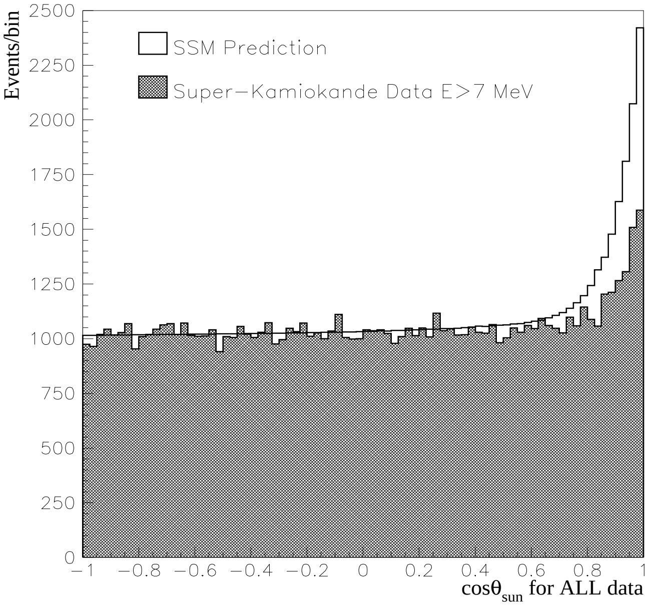

Fig. 1: The peak at 1 shows the strong correlation between the event directions and the Sun's position.

The measured event rate above an energy threshold $E_{\text{threshold}}$ is used to infer the total number of ^8B neutrinos at all energies which must be incident on Super-Kamiokande. The resultant preliminary total neutrino fluxes from both independent analysis groups are shown in Table 2. The two groups processed different quantities of data, have much different event filtering and reconstruction algorithms,

Table 1: Measured signal rates (statistical and systematic errors) and theoretical predictions above several energy thresholds

Preliminary Independent Results Using 22.5 kton fiducial volume			
$E_{threshold}$ (MeV)	Signal Excess (events)	(events/day)	SSM BP92 / BP95 Rate (events/day)
All data, 148.07 day sample			
6.5 MeV	2796 ± 128.0	18.884 ± 0.864 ± 0.933 (syst)	42.81 / 49.81
7.0 MeV	2436 ± 111.0	16.452 ± 0.750 ± 0.803 (syst)	35.93 / 41.80
8.0 MeV	1757 ± 86.0	11.866 ± 0.518 ± 0.590 (syst)	23.48 / 27.31
Day data, 70.17 day sample			
6.5 MeV	1330 ± 86.0	18.155 ± 1.226	42.81 / 49.81
7.0 MeV	1177 ± 75.0	16.774 ± 1.069 ± 0.980 (syst)	35.93 / 41.80
8.0 MeV	903 ± 57.5	12.869 ± 0.819	23.48 / 27.31
Night data, 77.90 day sample			
6.5 MeV	1462 ± 94.5	18.768 ± 1.213	42.81 / 49.81
7.0 MeV	1257 ± 82.0	16.137 ± 1.053 ± 0.942 (syst)	35.93 / 41.80
8.0 MeV	848 ± 63.5	10.886 ± 0.815	23.48 / 27.31

and have different overall efficiencies. The effective live times of each data set are given at the bottom of Table 2. Both groups produce similar results, which provides a consistency check on the analyses.

Table 2: Comparison of solar neutrino flux results from two independent analyses

Preliminary Total ^{8}B Flux Implied from Measurement Above $E_{threshold}$		
$E_{threshold}$ (MeV)	Total Implied ^{8}B Fluxes ($\times 10^6 \frac{\nu}{cm^2 s}$)	
± (statistical error) ± (systematic error)		
	Official Results	**Independent Results**
6.5	$2.65\,{}^{+0.09}_{-0.08}\,{}^{+0.14}_{-0.10}$	2.51 ±0.11 ±0.13
7.0	$2.70\,{}^{+0.09}_{-0.08}\,{}^{+0.15}_{-0.10}$	2.61 ±0.12 ±0.13
Effective live time	201.6 days	148.2 days
BP95 SSM Flux	6.62	

In addition to measuring the total flux of solar neutrinos, we can look for a time dependence of the measured flux. MSW enhanced neutrino flavor oscillations in the Sun (Wolfenstein, 1978 and Mikheyev and Smirinov, 1986) is one explanation for the apparent deficit of solar neutrinos. In this case, some of the neutrinos are changed from ν_e to another flavor (such as ν_μ). When the neutrinos travel through the Earth, the ν_μ can oscillate back into ν_e. The flux of ν_e will then be higher at night than during the day. We look for this ν_e regeneration in the Earth by computing the fractional flux difference for the day and night data as shown in Table 3.

The two independent group's preliminary total flux and day/night results are in good agreement. Although the two groups are using completely different vertex fitters, energy reconstruction, and event selection, getting the same answer from both groups boosts our confidence in the results from this experiment.

CONCLUSIONS

Super-Kamiokande has confirmed the apparent deficit in the total flux of neutrinos from the Sun. The preliminary measurement is low compared to the SSM calculations (BP95) of 6.62 $\times 10^6 \frac{\nu}{cm^2 s}$ for the

Table 3: Comparison of day/night flux differences

Preliminary Day versus Night Fluxes			
$E_{\text{threshold}}$	Volume	$\frac{D-N}{D+N}$	
(MeV)	(kton)	**Official Results**	**Independent Results**
6.5	22.5	+0.004 ± 0.031 ± 0.017	-0.017 ± 0.047
7.0	22.5	+0.004 ± 0.033 ± 0.017	+0.019 ± 0.046

^{8}B flux. In order to gauge the impact of these new solar neutrino results, a comparison is made against the most recent published results from the Kamiokande experiment, our predecessor. The Kamiokande results (Fukuda, 1996 and Hirata, 1991) are shown in Table 4. The Super-Kamiokande results presented in Tables 2 and 3 agree with the previous results, but have much smaller errors.

Table 4: Prior experimental solar neutrino results

Previous Results from Kamiokande (680 m^3)	
Total Flux (E> 7 MeV)	$2.82\ ^{+0.25}_{-0.24} \pm 0.027 \times 10^6\ \frac{\nu}{\text{cm}^2\text{s}}$
$\frac{D-N}{D+N}$ (E> 9.3 MeV & E> 7.5 MeV)	+0.08 ± 0.11 ± 0.03

It is apparent from the measured fluxes from the DAY and NIGHT data samples, that we have no statistically significant day/night flux difference. The large angle MSW oscillation solution predicts a day/night flux difference (the ‘day/night effect’) which can be as large as 50%. The current data sample does not have the statistical accuracy to completely rule out the large angle solution yet.

These are the first (preliminary) solar neutrino results from Super-Kamiokande. We will continue to collect data and perform two independent analyses of the data. We need to better understand our energy scale in order to reduce the systematic errors on the flux measurement. The next step will be to study the differential energy distribution of the solar neutrinos. We will look for any visible spectral distortions which may point towards new neutrino physics. Such a distortion is predicted by the nonadiabatic MSW flavor oscillation solution. Modifications can be made to the Standard Solar Model which lead to different neutrino fluxes. They can not, however, produce a distortion to the neutrino energy spectrum. Using both the day/night flux difference and the measured energy spectrum, Super-Kamiokande should provide strong evidence for or against neutrino flavor oscillations.

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