1013: Results from Super-Kamiokande

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Abstract. 300 days of data taking with the Super-Kamiokande detector give preliminary new constraints on neutrino oscillation parameters. 4400 solar neutrinos were detected with energies between 6.5 MeV and 20 MeV. No evidence for a day/night effect or spectrum distortion is observed so far. The preliminary value for the observed flux is $2.44^{+0.06}_{-0.06}(stat.)^{+0.25}_{-0.09}(sys.) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$. A preliminary $\nu_\mu \rightarrow \nu_\tau$ analysis of our atmospheric neutrino data indicates Δm^2 of order a few times 10^{-3} and a large mixing angle.

1 The Super-Kamiokande Experiment

Super-Kamiokande (SK) is a 50 kt water cherenkov detector built and run by a Japanese-American collaboration. Data taking 1000 m (2700 MWE) underground in the Kamioka Mining Company's Mozumi Mine 30 km south of the Japan Sea port city of Toyama started on April 1^{st} 1996. Apart from its neutrino related physics program SK sets new limits on the proton lifetime.

The cylindrical detector volume is divided into an inner and an outer detector (ID and OD), separated by a light barrier. The 32.5 kt ID is 36.2 m high, has a diameter of 33.8 m and is viewed by 11146 20 inch photomultiplier tubes (PMT). The OD completely surrounds the ID with > 2 m of water viewed by 1885 8 inch PMTs. Together with 55 cm of dead volume inside the light barrier this amounts to a water shield of > 2.6 m all around the ID.

Vital for SK is its water purification system (WS), which maximizes water transparency and minimizes natural radioactivity. The equivalent of one detector volume is recirculated through it in about one month. By the end of May 1996 changes in the attenuation length for cherenkov photons had dropped to the 1% level. Special precautions are taken to prevent admission of radon into the tank water, since the β-decay of ^{214}Bi in its decay chain is a serious source of background at low energies. The current level of radon activity is $<$ 5 mBq - a factor 100 lower than in Kamiokande.

PMT signals from the ID are processed in custom made ATM boards that digitize time and charge of PMT hits. The boards are self-triggering with a threshold of 1/4 photo electron (PE) equivalent. A readout of the experiment is initiated when a certain number of PMTs receive hits within 200 ns. To avoid dependency of the detector trigger threshold on changing PMT noise levels the corresponding signal is AC-coupled into a discriminator. Current trigger thresholds for the ID correspond to 29 and 31 hit PMTs, the lower one implying an energy threshold of 5.5 MeV. The corresponding trigger rates are

$10 - 12$ Hz and 4.3 Hz. OD-triggers are generated independently at a rate of 2.7 Hz. A 25 hit threshold is just becoming operational in an effort to lower the analysis threshold for solar neutrinos. Data are collected at a rate of 10 Gbytes/day. Calibration efforts limit the livetime of the experiment to 85% over the whole period of operation since April 1^{st} 1996.

2 ID Calibration Procedures

Calibration of the ATM electronic boards is done with a standard calibrated charge/time generator. The timing range spans $1.2\,\mu$s with 0.3 ns resolution and charge is recorded up to 550 pC with 0.2 pC resolution. Charge measurement reaches overflow at the level of 250 PE.

Relative gains of ID PMTs are balanced using light from a scintillator ball driven by a Xe flashlamp. After adjustment the spread in gain amounts to 7%. For timing calibration the short pulse of a nitrogen laser is diffused from the center of the ID. The average timing resolution of the inner detector PMTs is found to be 3 ns at the 1 PE level, reaching a limit of 0.6 ns at about 100 PE. Energy calibration depends on the energy range of interest and is discussed in the corresponding analysis section.

3 Solar Neutrinos

Two of the reactions in the solar fuel cycle produce neutrinos with energies above 2 MeV: β-decay of ^{8}B and proton capture on ^{3}He. Predictions for their rates are inferred from solar modelling (SM). The rate of ^{3}He-neutrinos is expected to be $< 10^{-3}$ that for ^{8}B neutrinos, which itself constitutes only $\sim 10^{-4}$ of the total flux of ν_{sol}. Thus only the ^{8}B neutrinos are accessible to an experiment like SK with a threshold of ~ 5 MeV. Their spectrum ends at 14.1 MeV, its shape being independend of solar physics [1].

The data discussed here were taken between May 31^{st} 1996 and June 23^{rd} 1997. The accumulated livetime is 306.3 days. The fiducial volume for solar neutrino (ν_{sol}) and atmospheric neutrino analysis contains 22.5 kt of water. It is defined by a minimum distance of 2 m from the ID PMT surfaces.

Background to the ν_{sol} analysis has three main sources. Cosmic ray muons may produce radioactive spallation products. Decays of spallation products are identified using their space and time correlation with preceeding muons. Deadtime introduced amounts to 20%, while the background is cut by 43%. γ-rays originating in the surrounding rock or PMT glass produce an excess of events near the confines of the detector. Events for which their back projected track intersects with the rock within 5 m are removed from the sample at the cost of 7.8% deadtime, yielding a further reduction of background by 30%. Radon decay events can not be isolated.

The analysis discussed in this contribution is the first ν_{sol} analysis with its energy scale based on SK calibration with a small linear accelerator for electrons (LINAC). Single electrons are injected into the tank at various radii and depth. At each position data are taken at discrete electron energies ranging from 5 to 16 MeV. Energy definition by the LINAC system is better than the 0.5% resolution of the Germanium detector used to calibrate it. Only two LINAC positions in the ID were completed in time for the analysis discussed here. After careful evaluation the energy scale for ν_{sol} events was shifted by $\sim$ 2% from what had previously been inferred from data taken with a γ-ray source. Subsequent LINAC measurements at other points are consistent with the initial two and validate this shift. Yet the systematic error on the ν_{sol}-flux is currently dominated by energy scale (+9.9%) and resolution (-3.1%). These errors have less impact on relative measurements like day/night (D/N) and seasonal variations. Vertex and direction fitting contribute -1.3% and +1.7% respectively. All other systematics are estimated to be less than 0.7% bringing the total to $^{+10.1\%}_{-3.5\%}$ for the flux measurement.

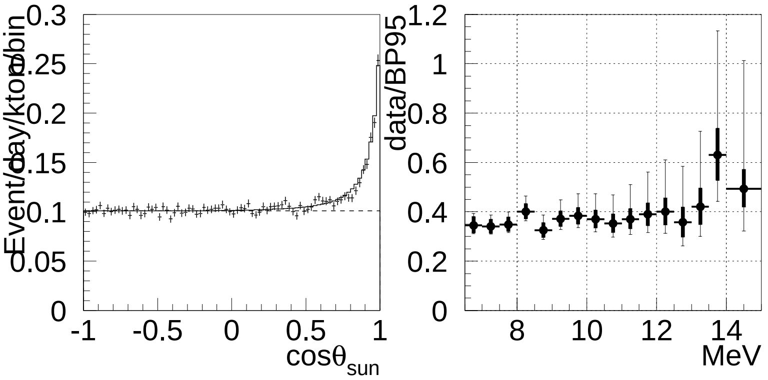

Fig. 1. 4400 ν_{sol} with energies 6.5 – 20 MeV from 306 d of SK data and their spectrum, normalized to the prediction from BP95

The left side of figure 1 shows the distribution of directions relative to the direction to the sun in the final sample. Of its almost 60000 events with energies from 6.5-20 MeV 4400 are in the peak towards the sun. The flux value extracted from the fit (histogram) to the data is $2.44^{+0.06}_{-0.06}(stat.)^{+0.25}_{-0.09}(sys.) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$. Comparison to the solar model of Bahcall and Pinsonneault[2] (BP95) yields $0.368^{+0.010}_{-0.009}(stat.)^{+0.037}_{-0.013}(sys.) \times$ BP95. The measured D/N asymmetry $(D - N)/(D + N)$ is $-0.017 \pm 0.026(stat.) \pm 0.017(sys.)$. The right side of figure 1 shows the measured energy spectrum normalized to the ^{8}B neutrino spectrum with BP95 normalization. The inner part of the error bars represents the statistical error, the outer part the systematic error estimate. No deviation from uniform suppression can be inferred.

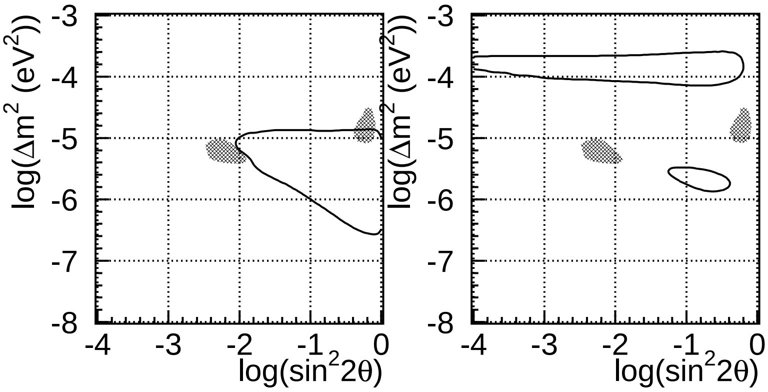

Fig. 2. Exclusion plots based on 300 d of SK D/N (left) and spectral (right) data

Based on these results 90% CL exclusion plots for neutrino mixing parameters in the MSW region are generated employing a χ^2-method. In figure 2 these are shown together with the 95% CL allowed regions obtained by Hata and Langacker[3] from a combined fit to older solar neutrino data from various experiments (shaded areas). The exclusion plot on the right is derived purely from the spectral information without constaint on the overall flux. For the D/N plot on the left the nighttime data were further subdivided into five $\cos(\theta_{zenith})$ bins with θ_{zenith} being the zenith angle of the momentary position of the sun. Vacuum oscillation parameters too are further constrained.

4 Atmospheric Neutrinos

Primary cosmic rays impinging on the atmosphere produce hadronic showers. Atmospheric neutrinos (ν_{atm}) originate from the decays of secondaries in these showers. For neutrino energies below 1 GeV almost all ν_{atm} stem from pion decay. That leads to the prediction $r = (\nu_\mu + \overline{\nu}_\mu)/(\nu_e + \overline{\nu}_e) \approx 2$. Interest in ν_{atm} was sparked by the observation that in all high statistics experiments this ratio differed from expectation. Since predictions for the absolute rate of ν_{atm} are still rather uncertain it remains unclear whether this anomaly reflects a lack of ν_μ or an excess of ν_e. Yet for the ratio r large parts of these uncertainties cancel out and predictions by various authors agree within 5% Thus the double ratio $R = r_{Data}/r_{MC}$ has become the focus of attention.

Like proton decay, neutrino interactions produce contained events, i.e. no particle enters through the OD. With muons losing about 200 MeV /m in water high energy muons from a ν_μ interaction may exit from the detector. Thus two event samples are collected from the data stream for the ν_{atm} analysis: Fully contained events (FC), for which no evidence of associated entering or exiting particles is seen, and partially contained events (PC), for which one exiting track is allowed. Through-going and stopping muons are rejected. Vertex position and direction are fitted and the fit results are used to cross-check the projected entrance region for unwanted signs of entering particles. About 30 FC/d and 20 PC/d from this automated selection are subsequently scanned by specialists. Cuts on energy and fiducial volume (22.5 kt) establish the final PC and FC samples. Energy calibration is extended to high energies by means of a tracklength correlation obtained from stopping muons, mass reconstruction for neutral pions and a fit to the spectrum of decay electrons from stopping muons. FC events are further subdivided into so-called sub-GeV and multi-GeV events by a cut on visible energy at 1.33 GeV. The minimal lepton momenta required for events to enter into the sub-GeV sample are 100 MeV for electrons and 200 MeV for muons.

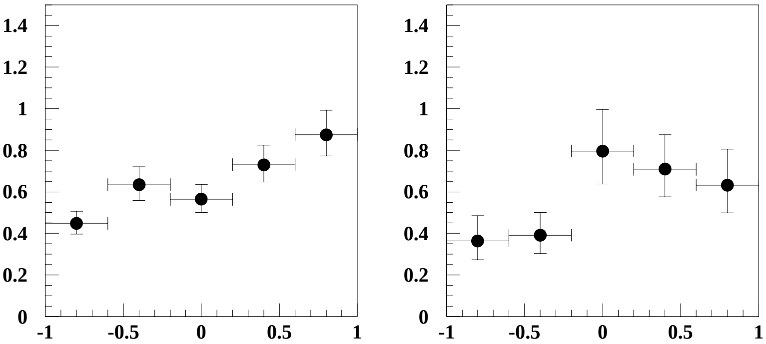

Fig. 3. Zenith angle dependence of R for 326 d of SK sub-GeV (left) and multi-GeV+PC (right) data. Horizontal axis is $\cos(\theta_{zenith})$, vertical is R

In charged current (CC) reactions on the nucleons in the detector water the outgoing lepton preserves the lepton flavor of the interacting neutrino. To identify the lepton flavor events are classified as showering or non-showering[4], introducing systematic errors of 2% on the sub-GeV sample and 4% on the multi-GeV sample. PC events are a 97% pure ν_μ sample. Pion production in the interaction process gives rise to multi ring events. To obtain the cleanest possible sample of CC quasi-elastic scattering events only single ring events are used, giving rise to a 4% error from ring counting. Systematic errors arising from uncertainties in the CC and NC interaction cross sections amount to 3.6% and 2-3% respectively, bringing the estimated total systematic errors to 8.2% on the sub-GeV data and 10.7% on the combined multi-GeV+PC samples.

The preliminary result for R from 325.8 d of ν_{atm} observation with SK is $0.604\,^{+0.065}_{-0.058} \pm 0.018 \pm 0.065$. The errors given are the statistical error of the data sample, MC sample, and the systematic error.

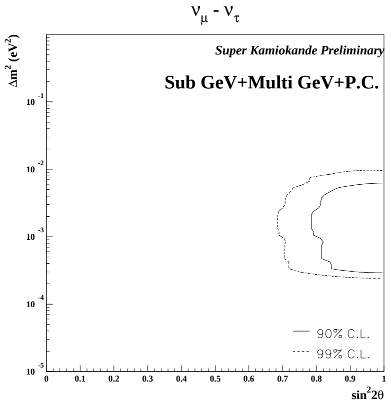

Fig. 4. 90 and 99% CL allowed regions for $\nu_\mu \rightarrow \nu_\tau$ oscillation from 326 d of SK atmospheric neutrino data

Figure 3 shows the dependence of R on the zenith angle for the sub-GeV and multi-GeV+PC samples. $\cos\theta_{zenith} = 1$ corresponds to downward going events. The zenith angle dependence of the sub-GeV data forces Δm^2 down to a few times 10^{-3} in a $\nu_\mu \rightarrow \nu_\tau$ oscillation analysis as shown in figure 4.

5 Conclusion

Solar neutrino observation with SK entered a new era with the advent of the first LINAC data. Oscillation analysis so far remains inconclusive. Extending the spectal range of this measurement to lower neutrino energies is a clear priority for SK

Atmospheric neutrinos show a zenith angle dependence when comparing the observed to expected μ-like/e-like event ratio. In the context of $\nu_\mu \rightarrow \nu_\tau$ oscillations our measurement suggests a large mixing angle and Δm^2 of order a few times 10^{-3}. Suitable long baseline experiments will soon explore large parts of this parameter space.

References

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