Low Energy Neutrino Physics at Super-Kamiokande

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Abstract. In spite of intensive studies of solar 8B neutrinos – which resulted in the first evidence that the flavour of solar neutrinos oscillates – the characteristic, expected transition between vacuum oscillations below and matter-dominated oscillations above 3 MeV remains thus far elusive. Also, the only direct demonstration of matter effects on solar neutrino oscillations, the day/night asymmetry, has not been observed yet. After a review of past measurements, Super-Kamiokande’s future solar and supernova neutrino physics sensitivity is discussed, in particular in light of the possibility of Gadolinium doping.

1. Introduction
Super-Kamiokande, a 50kton cylindrical water Cherenkov detector located about 3 km w.e. underground, observes solar neutrinos via elastic scattering off electrons. About 11,000 20” photomultiplier tubes view the innermost 32 kton and yield about six detected photo-electrons per MeV of electron energy. As a consequence only the high energy 8B and hep neutrinos can be observed. However, the direction and energy of the recoiling electrons are reconstructed, so neutrino interactions are recorded in real-time and point back to the sun. Also, the large fiducial mass of the innermost 22.5kton of the detector results in a large solar neutrino interaction rate of about 15 events/day above 5 MeV after event selection. Consequently, the first phase of the experiment, Super-Kamiokande-I collected about 22,000 solar neutrino events in about five years – by far the largest sample of solar neutrinos in the world. Since all solar neutrino flavors undergo elastic scattering with electrons – although the cross section for the electron flavor is enhanced – a comparison of the elastic scattering rate at Super-Kamiokande with the charged-current interaction rate of purely electron-flavored solar neutrinos with deuterons at the Sudbury neutrino observatory [1] provided the first evidence of solar neutrino flavor transformation.

2. Super-Kamiokande-I Results
Super-Kamiokande-I measured the 8B neutrino flux to be \( \Phi = 2.35 \pm 0.02 \text{(stat)} \pm 0.08 \text{(syst)} \times 10^6 \text{cm}^2 \text{sec}^{-1} \) [2]. The (total) energy threshold for the recoil electrons was 5 MeV. There appears to be no significant distortion in the recoil electron spectrum (see Figure 1). The solar neutrino interaction rate was searched for various time variations; the only significant time variation found is caused by the 1.7% orbital eccentricity of the Earth producing a 7% variation simply from the inverse square radius law. From the solar neutrino data, the eccentricity was measured to be \( 2.1 \pm 0.3 \% \text{(syst)} \), the perihelion shift seen in the neutrino data with respect to the true perihelion is \( 13 \pm 18 \) days. Among the time variations the so-called day/night asymmetry \( A_{DN} = \frac{\Phi_D - \Phi_N}{0.5(\Phi_D + \Phi_N)} \) was most carefully studied; a non-zero value would be a sign of Earth matter effects on solar neutrino
Figure 1. Recoil Electron Spectral Distortion for Super-Kamiokande-I (Left), Super-Kamiokande-II (Middle), and Super-Kamiokande-III (Right). The ratio of the measured and the expected solar neutrino elastic scattering rate from a $^8$B neutrino flux of $2.33 \times 10^6$/cm$^2$/sec and a hep neutrino flux of $15 \times 10^3$/cm$^2$/sec is displayed. The shaded area is the contribution from just the $^8$B neutrino flux. The dark-colored band represents the value and statistical uncertainty of the combined rate 5-20 MeV (7-20 MeV).

oscillation (usually a regeneration of electron-flavor neutrinos). The straight day/night asymmetry was measured to be $A_{DN} = -0.021 \pm 0.020$(stat)$\pm 0.012$(syst). Also, a fit to the amplitude of the expected day/night variation using the solar neutrino oscillation parameters in the Large Mixing Angle region yields $-0.017 \pm 0.016$(stat)$\pm 0.012$(syst)$\pm 0.0004$(osc) when expressed as a day/night asymmetry.

3. Super-Kamiokande-II Results
The second phase, Super-Kamiokande-II, confirmed the results of Super-Kamiokande-I. Solar neutrinos were detected for recoil electrons above 7 MeV of (total) energy and the $^8$B neutrino flux of $\Phi = 2.38 \pm 0.05$(stat)$\pm 0.015$(syst)$\times 10^6$/cm$^2$/sec [3] agrees with Super-Kamiokande-I much better than expected even from statistical uncertainties alone (see Figure 1). This is particularly remarkable since Super-Kamiokande-II has only 46.5% of the photomultiplier tubes of Super-Kamiokande-I, those photo detectors are enclosed in blast shields which remove a few percent of the light and add radioactive background. Furthermore, the entire analysis had to be rebuild including event reconstruction, event selection and detector calibration. Like Super-Kamiokande-I, the second phase found no distortions (see Figure 1) in the recoil electron spectrum. The day/night asymmetry was measured to be $A_{DN} = -0.063 \pm 0.042$(stat)$\pm 0.037$(syst) – also in good agreement with Super-Kamiokande-I. There is no significant time variation of the elastic scattering rate of any kind, except the seasonal variation due to the inverse square radius law. Super-Kamiokande-I and II together span an entire 11 year solar cycle, there’s no significant dependence of the $^8$B solar neutrino flux on this cycle (see Figure 2).

4. Super-Kamiokande-III
The third phase of Super-Kamiokande restored the full number of photomultiplier tubes to the experiment. The preliminary Super-Kamiokande-III flux ($\Phi = 2.31 \pm 0.05$(stat)$\times 10^6$/cm$^2$) and spectrum shown in Figure 1 agrees well with the previous phase within statistical uncertainty only. In spite of the radioactivity introduced by the blast shields, the background level near 5 MeV is significantly lower than Super-Kamiokande-I in the center of the detector due to an improved
water circulation pattern which suppresses the transport of Radon to the center. Consequently, the statistical uncertainty of the event rate between 5 and 5.5 MeV of Super-Kamiokande-III is comparable to Super-Kamiokande-I in spite of a factor of about six less exposure! While the trigger efficiency at 5 MeV is 100% (indeed at the very end of Super-Kamiokande-III it was 100% at 4.5 MeV) the hardware trigger threshold does not allow a significant lower analysis threshold than SK-I.

5. Super-Kamiokande-IV Trigger

Last September, the Super-Kamiokande electronics and data acquisition was modernized and redone. To fully take advantage of the lower radioactive background of the center of Super-Kamiokande-III with respect to Super-Kamiokande-I there is no event trigger anymore. Instead, data is acquired continuously and events are extracted by a software trigger system from this data stream. This system allows for a secondary data stream apart from the simple coincidence trigger which was previously constructed by hardware and is now emulated by software. The new Wide-band Intelligent Trigger system (WIT) is a computer farm which simultaneously selects and reconstructs very low energy events by applying the timing coincidence after subtraction of the time of flight from the vertex to the PMTs. It consists currently out of four 3GHz quad-core CPUs fed directly via 10GBit/sec fast ethernet lines by the DAQ computers.

The WIT system was tested with a Ni-Cf source inserted at the positions (0.4,-0.7,-17.1)m, (0.4,-0.7,-16.1)m, (0.4,-0.7,-15.1)m, (0.4,-0.7,-12)m, (0.4,-0.7,0)m, and (0.4,-0.7,15.1)m. These positions were selected to probe near the edge of the fiducial volume (±16.1m). The trigger efficiency at 3 MeV is around 85%, the trigger efficiency at 4 MeV around 93%.

6. Day/Night Asymmetry

The solar neutrino oscillation parameters predict a fairly small day/night asymmetry (about 1.5%). To eventually measure such a small asymmetry requires excellent control of systematic effects and a very large data sample. The well-calibrated Super-Kamiokande detector with its large fiducial mass of 22.5kton is at present the only detector that can probe such small asymmetries. The fit to the amplitude of the day/night variation was only performed for the Super-Kamiokande-I data (1.6% statistical uncertainty); we expect the Super-Kamiokande-II data yield a (statistical) precision of 3.4% with this method. The $A_{DN}$ uncertainty of the Super-Kamiokande-III data should be 2.9%, so Super-Kamiokande-I/II/III combined can determine
The present estimate of the systematic uncertainty for Super-Kamiokande-I is 1.3%, however, it is a rather conservative estimate based on the idea of simply splitting the data into a day and a night sample. The dominant source of systematic uncertainty to day/night variation is the directional dependence of the energy scale. Multiple Coulomb scattering smears the direction of the recoil electrons by 20 to 30 degrees, so a varying energy scale can only explain slow day/night variations while at least some of the flavor conversion variation from the matter effects of the earth happens much faster. Using calibration data taken with a deuterium-tritium (DT) neutron generator (which produces $^{16}$N in situ via a charge-exchange reaction with $^{16}$O) this systematic effect can be verified and understood. If this is indeed a correct description of the effect, the amplitude fit to the day/night variation would be more robust than the estimated 1.3%. So a total uncertainty of 1.4% might be reached assuming the systematic uncertainty can be reduced by 50%.

7. Spectral Distortion

The predicted spectral distortion in the elastic scattering rate (due to the transition of matter-driven oscillations to vacuum-driven oscillations at around 3 MeV) is on the order of 10% in the energy region 4 to 15 MeV. Assuming the observed background level in the central 13.3kton of Super-Kamiokande-III, a fiducial mass of 13.3 kton from 4 to 5.5 MeV, and a fiducial mass of 22.5kton for energies above 5.5 MeV, Super-Kamiokande can resolve this 10% effect within twelve years at three standard deviation significance. If we can further improve the water circulation pattern to suppress Radon transport to take advantage of the full fiducial mass of 22.5ktons for all energies, the same significance will be achieved in ten years. The energy-bin correlated systematic uncertainties are rather important for the spectral sensitivity: if they can be reduced by 50%, the same significance is reached within eight years (assuming full fiducial mass at all energies). This systematics is mostly limited by position dependence of the Super-Kamiokande energy scale. This energy scale is defined by injecting single, downward-going electrons into Super-Kamiokande with an electron linear accelerator [5]. The energy can be tuned between 4.5 and 16.5 Mev. In addition, the DT neutron generator data also defines the energy scale at a single energy, but uniform in direction, with higher statistics, and at more positions. Furthermore, various laser light injectors at different wavelength help with understanding the optical properties of the detector to better control energy-scale related systematic uncertainties.

8. Conclusion

Even in the thirteenth year of measuring solar neutrinos, Super-Kamiokande still impacts solar neutrino physics. The new, threshold-less electronics and data acquisition system in conjunction with better calibration and control of systematic effects will help reveal the role of solar and terrestrial matter effects in solar neutrino oscillations.

References

[1] Q. R. Ahmad et al., Phys. Rev. Lett.87: 071301, (2001)
[2] J. Hosaka et al., Phys.Rev.D73: 112001, (2006)
[3] J. P. Cravens et al., Phys.Rev.D78: 032002, (2008)
[4] E. Blaufuss et al., Nucl.Instrum.Meth.A458: 638, (2001)
[5] M. Nakahata et al., Nucl.Instrum.Meth.A421: 113, (1999)