Solar and Atmospheric Neutrinos in Super-Kamiokande

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Abstract. The Super-Kamiokande (SK) water Cherenkov detector has been operating for nearly 12 years collecting data for the study of both solar and atmospheric neutrinos as well as supernova neutrinos (and relic supernova neutrinos) and nucleon decay. The experiment has undergone three operating phases during the full running period: SK-I (40% photocathode coverage), SK-II (20% coverage), and SK-III (40% coverage). Soon, the experiment will move into its fourth phase when the data acquisition electronics are upgraded in late 2008. Presented here are neutrino oscillation results from SK-I and SK-II solar and atmospheric data, and a preliminary look at data from SK-III. Also discussed briefly is the upcoming electronics upgrade that will carry the experiment into its fourth phase.

1. Introduction
Super-Kamiokande [1, 2] is a 50,000 ton (22,500 ton fiducial) water Cherenkov detector located 1000 m underground at the Kamioka Observatory of the Institute for Cosmic Ray Research, University of Tokyo. The detector is cylindrical: 42 m high and 39.3 m in diameter. Neutrino interactions in the water are viewed by 50-cm photomultiplier tubes (PMTs) facing inward and distributed evenly on the entire inner detector (ID) surface. The inner volume is surrounded by an outer detector (OD) which is instrumented with smaller 20-cm PMTs facing outward to aid in identification and rejection of non-neutrino-induced events and events arising from interactions that took place in the rock surrounding the detector.

A broad range of energies is studied with the SK detector, from a few MeV up to $\mathcal{O}(\sim \text{TeV})$. In the low energy region below $\sim 20$ MeV, solar neutrino interactions are detected by neutrino-electron scattering. At higher energies, atmospheric neutrino interactions covering 5 orders of magnitude are detectable by neutral- and charged-current neutrino-nucleon scattering.

The Super-Kamiokande running periods are divided into three parts. SK-I ran from 1996 until November 2001, when an accident destroyed more than half of the PMTs. The detector was rebuilt with half the PMT density (and therefore half the photocathode coverage) and resumed data-taking for its second phase from 2003 through October 2005. Restoration of the full 40% photocathode coverage was completed by mid-2006; the SK-III phase has been collecting data since July 2006.

1.1. SK-IV Data Acquisition
In August 2008, the third running period will end in order to upgrade the data acquisition (DAQ) electronics. The upgraded electronics will simplify detector operations by unifying the
readout scheme for the inner and outer detectors (previously distinct). In addition, we expect both increased reliability (due to fewer discrete components) and increased performance (in the form of improved energy resolution, improved multiple-hit capability, lower single photo-electron hit thresholds, and improved supernova burst capability). The ethernet-based readout will allow for increased bandwidth and reduced deadtime.

In the DAQ system employed for SK-I, II, and III, a hardware trigger (issued when the number of PMT hits in a 200 ns timing window exceeds a threshold) was utilized to reduce the amount of data sent from the readout modules to the front-end DAQ computers. In the SK-IV DAQ, no hardware trigger is used. Instead all PMT hits are sent to the front-end computer by a periodic timing signal, and software triggers are then applied to select interesting event windows. This new scheme is a novel approach to high energy physics data acquisition; it provides much greater flexibility in triggering than previous DAQ systems have allowed.

2. Solar Neutrinos
At low energies, Super-Kamiokande is sensitive primarily to neutrinos from the \(^8\)B branch of the pp nuclear fusion chain in the Sun. The neutrinos produced in this branch range in energy from less than 1 MeV to near 20 MeV. At low energies, radioactive backgrounds dominate making it very difficult to select solar neutrino events. Above approximately 4 MeV, these are detectable in SK by Cherenkov light from a recoiling atomic electron in a \(\nu - e^-\) scatter. The energy of the recoil electron and its direction relative to the Sun are reconstructed; electrons that were scattered by neutrinos point in a direction that is correlated with the Sun. This is shown for SK-III data in Fig. 1.

![Figure 1](image1.png)

**Figure 1.** Angular distribution of solar neutrino event candidates. The elastic scattering peak is indicated by the shaded region, the background by the dotted region.

![Figure 2](image2.png)

**Figure 2.** Allowed oscillation parameter region obtained from a combined fit to experimental data from SK-I, SK-II, SNO, Homestake, SAGE, and GALLEX shown in blue. Overlaid in red is the KamLAND allowed region.

The original goal of the SK solar neutrino measurement was to look for flux-independent
Figure 3. SK-I (black dots) and SK-II (blue dots) solar neutrino flux compared to sunspot activity (pink dots) during the periods of SK-I and SK-II data-taking. No correlation with solar cycle minima or maximum is seen.

evidence of neutrino oscillations such as a difference of daytime and nighttime fluxes, seasonal variations of the flux, and/or spectrum distortion. Although no significant evidence for any of these has been observed, the non-observation has allowed Super-Kamiokande to help place a strong constraint on the neutrino oscillation parameters. Fig. 2 shows the 95% C.L. allowed region of oscillation parameter space for combined experimental data from SK-I, SK-II, SNO, and radiochemical experiments. Also shown is the KamLAND allowed region which strongly constrains the mass.

Because the SK-I and SK-II solar neutrino datasets span a time period comprising nearly one full solar cycle, it is possible to check for correlations with solar activity. No correlation is apparent, as shown in Fig. 3.

3. Atmospheric Neutrinos

Atmospheric neutrinos

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References