Super-Kamiokande Solar Neutrino Results and NSI Analysis

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Abstract. Super-Kamiokande (SK) detects the Cerenkov light from elastic scattering of solar $^8$B neutrinos with electrons in its ultra-pure water. The directionality, energy, and timing of the recoil electrons determines the interaction rate, the flight path, as well as the energy dependence of the $^8$B neutrinos’ electron-flavor survival probability $P_{ee}$. While the $P_{ee}$ below 1 MeV is equivalent to averaged vacuum neutrino flavor oscillations, the $P_{ee}$ above 7 MeV is suppressed by the Mikheyev-Smirnov-Wolfenstein (MSW) resonance resulting from the interaction of the solar neutrinos with solar matter. In the same way, Earth matter effects influence $P_{ee}$, leading to an apparent Day/Night effect. Non-standard interactions (NSI) extend the MSW model to include interactions between the quarks in matter and neutrinos, thereby modifying $P_{ee}$. We present the signatures of matter effects on solar neutrinos in Super-Kamiokande and present limits on NSI parameters, in particular couplings to the down quark.

1. Introduction
Super-Kamiokande (SK)[1] is a 50 kton ultrapure water Cherenkov detector that has been running since 1996, and contains an inner detector and an optically separated outer detector which is used to veto cosmic muons. A wall cut significantly reduces the radioactive background from the PMT glass and shielding. The resulting fiducial volume is 22.5 ktons. Neutrinos are detected in SK through the Cerenkov light produced from electrons ($e^-$) recoiling due to the elastic scattering of the neutrino with the electrons in the water via the electroweak interaction. This process is well understood, has no energy threshold, and the energy spectrum of the recoil $e^-$ is strongly forward-peaked, allowing for separation of solar neutrino interactions which point to the sun from radioactive background which does not. SK is sensitive to the $^8$B neutrinos ($^8$B $\nu$) produced in the core of the sun in the pp fusion chain, and detects approximately 18 $^8$B $\nu$ per day in SK-IV (the current phase of the SK experiment[2]).

For the last 20 years, SK has been detecting real-time neutrino interactions, has good energy resolution for the recoil $e^-$, and has directional information of $^8$B $\nu$, giving many candidate events with which to study matter effects on $^8$B $\nu$ for various theories. Solar matter effects, such as MSW and NSI, are dependent on the matter density at the $e^-$ neutrino production point in the sun and affect the probability that the solar $e^-$ neutrino produced in the solar core will arrive at SK in the electron state ($P_{ee}$). The matter potential due to the matter density profile in the Earth along the zenith angle of the $^8$B $\nu$ flight path ($\cos\theta_z$) further modulates this probability through regeneration effects.
2. SK-IV Solar Neutrino Analysis Details

The Super-Kamiokande-IV (SK-IV) solar neutrino dataset now contains data from 2364.7 days of livetime (1142 day, 1223 night), which is approximately 700 more days of data collected since Neutrino 2014. Since then, the analysis has undergone several improvements including an extension of the fiducial volume in the 4.5-5.0 MeV$_{\text{kin}}$ bin to the full 22.5 ktons (the energy spectrum of the recoil $e^-$ is binned by their kinetic energy), and also a lowering of the threshold at which data is taken in order to increase the efficiency. This change in threshold results in an increase of efficiency in the lowest energy bin of the analysis (3.5-4.0 MeV$_{\text{kin}}$) from 89.4% to 98.7%, and the second lowest bin (4.0-4.5 MeV$_{\text{kin}}$) from 99.2% to 99.6%. The total livetime across all phases of SK is 5199.7 days for SK’s solar analysis, and approximately 84,000 solar neutrinos have been seen. For the SK-IV data set, the number of signal events extracted are 46,173.0 + 341.8 - 339.9 (stat), corresponding to a $^8$B flux of 2.326 ± 0.017(stat) ± 0.040(sys) [$10^6$/cm$^2$/s]

3. SK-IV Solar Neutrino Oscillation Analysis Details

With this high statistics sample of solar neutrinos we test various hypotheses, such as no neutrino oscillation, vacuum oscillation, MSW effects in the sun, and Day/Night asymmetry ($A_{D/N}$) due to matter in the Earth. It is also possible to study NSI of solar neutrinos with matter in the sun and Earth, discussed in the next section. To do this, SK uses the calculations for the $P_{ee}$ predicted by the hypothesis (and parameters) under testing to predict the recoil electron spectrum that should result in SK and compare with the spectrum from the collected data.

The solar neutrino $P_{ee}$, which is dependent on the oscillation parameters $\theta_{12}$, $\theta_{13}$, and $E/\Delta m^2_{21}$, is calculated for a set of production points in the solar core and along various trajectories, as well as the dependence of $P_{ee}$ on $\cos(\theta_z)$ at SK due to the Earth matter. Detector and solar neutrino model uncertainties are combined with the zenith dependent $P_{ee}$ to predict the recoil electron spectrum in SK. The SK solar neutrino oscillation results can be further combined with results from complementary experiments (the Sudbery Neutrino Observatory (SNO) detector[3], and the radiochemical experiments Homestake[4], SAGE/Gallex/GNO[5], and Borexino[6]). Super-Kamiokandes oscillations measurements are complemented with those of SNO: Super-Kamiokandes has the best measurement of $\Delta m^2_{21}$, and SNO has the best measurement of $\sin^2(2\theta_{21})$. Together, they place tight constraints on the allowed oscillation parameter space for solar neutrinos, as seen in Figure 1. The shaded regions correspond to oscillation parameters included at a confidence level of 3 $\sigma$, while the lines correspond to 4 and 5 $\sigma$ inclusion. The 1-D $\Delta \chi^2$ for the individual parameters are given on the opposite side of the corresponding axis. The SK and SNO $\chi^2$ values are combined by comparing the quadratic fit for $P_{ee}$ and $A_{D/N}$ between the two.

Both SK and SNO show strong evidence for the MSW matter transitions when compared to the vacuum consistent $P_{ee}$ for lower energy solar neutrinos seen by the radiochemical experiments. The transition region (below 7 MeV) between the vacuum dominated region and the MSW dominated region is being probed by SK. For an in-depth description of the details for the SK-IV solar neutrino candidate extraction and oscillation analyses (using 1664 days of livetime in SK-IV), please see the most recent SK paper on this analysis[2].

4. NSI between d-quarks and Solar Neutrinos detected by SK

The $P_{ee}$ in the transition region below 7 MeV in both SK and SNO data is flatter than expected. Models such as NSI could explain this behavior[7][8]. NSI extends the matter potential in the neutrino Hamiltonian allowing for non-zero terms of all entries of the 3x3 matter potential matrix. This corresponds to extra 4-fermion interaction vertices that allow the neutrinos to interact with quarks (u,d), and have flavor changing interactions with the charged leptons (e). Since atmospheric and accelerator neutrino beam data constrain the muon related NSI
parameters to be very close to zero, only the \( \epsilon_{ee}, \epsilon_{e\tau}, \) and \( \epsilon_{\tau\tau} \) parameters of the NSI matter potential matrix are allowed to be non-zero in this analysis. A 2-flavor potential is considered, following Friedland, Lunardini, and Pena-Garay\cite{7}, while still incorporating \( \theta_{13} \) effects. The following convenient parameterization is used: \( \epsilon_{f11}^I = \epsilon_{f \bar{e}e} - \epsilon_{f \bar{\tau}\tau} \sin^2(\theta_{23}) \) and \( \epsilon_{f12}^I = -2 \epsilon_{f e\tau} \sin(\theta_{23}) \), where \( f \) is the sum over interactions with u,d, and/or e. This is similar to the parameterization in Maltoni and Gonzalez-Garcia’s work\cite{8}, and can related by \( \epsilon_{f11}^I = -\epsilon_{fDF}/2 \) and \( \epsilon_{f12}^I = \epsilon_{fN}/2 \).

This analysis considered the following parameter space of standard neutrino oscillations: \( \sin^2(\theta_{13}) = 0.02, \sin^2(\theta_{12}) \in [0.186, 0.888], \) and \( \Delta m^2_{21} \in [10^{-5}, 2.0 \times 10^{-3}] \). In addition, a simplified model of the Earth was used, where the average density along the neutrino’s path through the Earth is considered: two average matter densities are assumed for neutrinos that pass through the Earth’s core, or the average mantle density for neutrinos passing only through the mantle. After the zenith dependent NSI \( P_{ee} \) is calculated, the analysis is the same as in [2] to generate the recoil e\(^-\) spectrum predictions and SNO polynomial coefficients, as well as to perform fits to the SK-I-IV (1664 days\cite{2}) data sets. Preliminary results are shown in Figure 2, where the confidence levels are determined after profiling over \( \Delta m^2_{21} \) and \( \theta_{12} \). Further work for this analysis is underway, including more coverage of the \( (\theta_{12}, \Delta m^2_{21}) \) parameter space, using the Preliminary Reference Earth Model (PREM)\cite{9} for modeling the Earth (the same model used in the SK solar oscillation analysis), and inclusion of KamLAND anti-neutrino data.

References
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