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Precise measurement of the solar neutrino day-night and seasonal variation in Super-Kamiokande-I

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The time variation of the elastic scattering rate of solar neutrinos with electrons in Super-Kamiokande-I was fit to the variations expected from active two-neutrino oscillations. The best fit in the large mixing angle solution has a mixing angle of $\tan^2\theta=0.55$ and a mass squared difference of $\Delta m^2=6.3\times 10^{-5}$ eV² between the two neutrino mass eigenstates. The fitted day-night asymmetry of $-1.8\pm 1.6(\text{stat})_{-1.2}^{+1.3}(\text{syst})\%$ has improved statistical precision over previous measurements and agrees well with the expected asymmetry of -2.1% .

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The combined analysis of all solar neutrino experiments [1,2] gives firm evidence for neutrino oscillations. All data are well described using just two neutrino mass eigenstates and imply a mass squared difference between $\Delta m^2=3\times 10^{-5}$ eV² and $\Delta m^2=1.9\times 10^{-4}$ eV² and a mixing angle between $\tan^2\theta=0.25$ and $\tan^2\theta=0.65$ [3]. This region of parameter space is referred to as the large mixing angle (LMA) solution. The rate and spectrum of reactor antineutrino interactions in the KamLAND experiment [4] are also well reproduced for these mixing angles and some of these Δm^2 . Over the Δm^2 range of the LMA, solar ⁸B neutrinos are $\approx 100\%$ resonantly converted into the second mass eigenstate by the large matter density inside the Sun [5]. Therefore, the survival probability into ν_e is $\approx \sin^2\theta$. However, because of the presence of Earth's matter density, the oscillation probability at an experimental site on Earth into ν_e differs from $\sin^2\theta$ during the night. Since our experiment is primarily sensitive to ν_e 's, this induces an apparent dependence of the measured neutrino interaction rate on the solar zenith angle (often a regeneration of ν_e 's during the night). In this paper we measure the neutrino interaction rate in two separate data samples (day and night) assuming the interaction rate to be constant within each data sample. From these rates we calculate a day-night rate asymmetry as in [2,3]. We then employ a maximum likelihood fit of the rate variation amplitude to the solar zenith angle dependence of the neutrino interaction rate. Herein, the statistical uncertainty is reduced by 25% compared to the rate asymmetry. It would require almost three more years of running time to obtain a similar uncertainty reduction with the conventional day-night rate asymmetry. After that, we fit the recoil energy spectrum and time variations of the solar neutrino flux to two-neutrino oscillation models varying $\tan^2\theta$ and Δm^2 . Finally, we combine these oscillation fits with other solar and reactor neutrino experiments.

Super-Kamiokande (SK) is a 50 000 ton water Cherenkov detector described in detail elsewhere [6]. SK measures the energy, direction, and time of the recoil electron from elastic scattering of solar neutrinos with electrons by detection of the emitted Cherenkov light. Super-Kamiokande started taking data in April 1996. In this report, we analyze the full

SK-I low energy data set consisting of 1496 live days (May 31st, 1996 through July 15th, 2001).

The solar neutrino interactions are separated from background events by taking advantage of the strong forward peak of the elastic scattering cross section. The arrival time of each solar neutrino candidate defines a solar direction. Using this direction, we calculate the angle θ_{sun} between the reconstructed recoil electron direction and the solar direction. The data sample is divided into $N_{\text{bin}}=21$ energy bins: 18 energy bins of 0.5 MeV between 5 and 14 MeV, two energy bins of 1 MeV between 14 and 16 MeV and one bin between 16 and 20 MeV. We use two types of probability density functions: $p(\cos\theta_{\text{sun}}, E)$ describes the angular shape expected for solar ν_e 's of recoil electron energy E (signal events) and $u_i(\cos\theta_{\text{sun}})$ is the background shape in energy bin i . Each of the n_i events in energy bin i is assigned the background factor $b_{i\kappa}=u_i(\cos\theta_{i\kappa})$ and the signal factor $s_{i\kappa}=p(\cos\theta_{i\kappa}, E_{\kappa})$. The likelihood

$$\mathcal{L}=e^{-(\sum_i B_i+S)} \prod_{i=1}^{N_{\text{bin}}} \prod_{\kappa=1}^{n_i} \left(B_i \cdot b_{i\kappa} + S \frac{MC_i}{\sum_j MC_j} \cdot s_{i\kappa} \right)$$

is maximized with respect to the signal S and the 21 backgrounds B_i . MC_i is the number of events expected in energy bin i using the flux and spectrum of ⁸B and hep neutrinos.

A simple determination of the day-night asymmetry is obtained by dividing the data sample into day and night and fit $\cos\theta_{\text{sun}}$ to each sample separately. Disregarding neutrino oscillations, the day rate corresponds to a ⁸B flux of $D=2.32\pm 0.03(\text{stat})_{-0.07}^{+0.08}(\text{syst})10^6/\text{cm}^2\text{s}$ and the night rate to $N=2.37\pm 0.03(\text{stat})\pm 0.08(\text{syst})10^6/\text{cm}^2\text{s}$. The rate asymmetry $A_{\text{DN}}=(D-N)/(0.5(D+N))=-2.1$

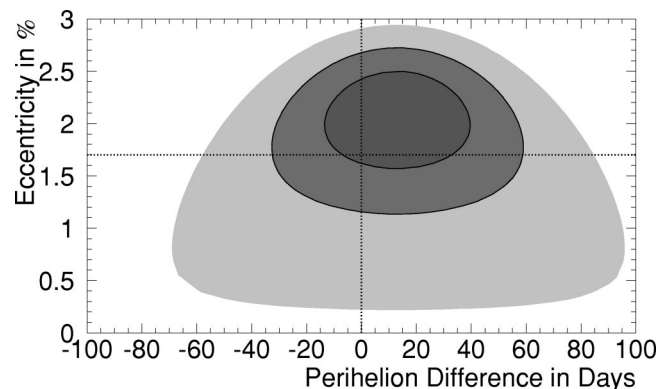


FIG. 1. Allowed regions for the eccentricity-induced seasonal solar neutrino flux variation at 68% (dark), 95% (gray), and 99.73% (light gray) C.L.

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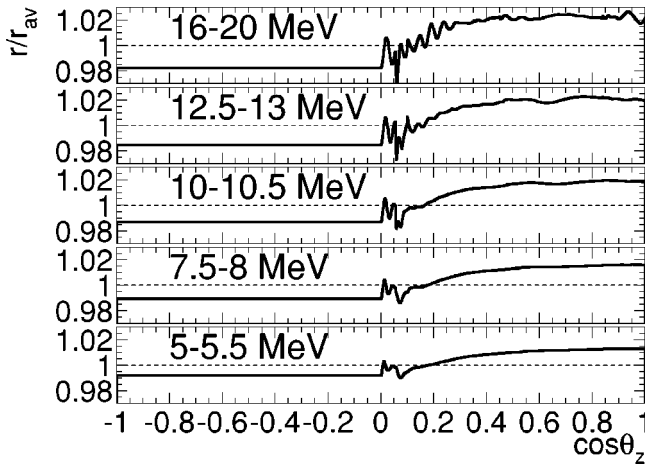


FIG. 2. LMA solar zenith angle variation shapes. The predictions are for $\Delta m^2 = 6.3 \times 10^{-5} \text{ eV}^2$ in the energy bins 16 to 20 MeV (top), 12.5 to 13 MeV, 10 to 10.5 MeV, 7.5 to 8 MeV and 5–5.5 MeV (bottom).

$\pm 2.0(\text{stat})_{-1.3}^{+1.3}(\text{syst})\%$ is consistent with zero. (The systematic uncertainty of A_{DN} takes into account systematic correlations between the day and night rates.) To take into account time variations in the likelihood fit, the signal factors are modified to $s_{i\kappa} = p(\cos \theta_{i\kappa}, E_{i\kappa}) \times z_i(\alpha, t_{i\kappa})$ where $t_{i\kappa}$ is the event time and α is an amplitude scaling factor. As a simple example, we measure the Earth's orbital eccentricity. Since the neutrino flux is proportional to the inverse square of the distance between Sun and Earth, the eccentricity induces a seasonal time variation. Below 6.5 MeV the background rates can fluctuate at time scales of several weeks or longer mainly due to changes in the radon contamination in water. Therefore, these energy bins are excluded from the eccentricity analysis by setting z_i to 1. To measure both the phase and amplitude of the variation, both the eccentricity and the perihelion are varied around the known values (1.7% and \approx January 3rd). Figure 1 shows the allowed ranges of parameters at 68%, 95%, and 99.73% C.L. Maximizing the likelihood with respect to the eccentricity, we measure the perihelion shift to be 13 ± 17 days which is consistent with zero. The amplitude of the neutrino flux variation is 1.51 ± 0.43 (consistent with one) times the amplitude expected from 1.7% eccentricity where the likelihood has been maximized with respect to the perihelion shift.

To study neutrino oscillation-induced time variations, we correct for this seasonal effect (with the nominal perihelion and eccentricity). After that, the additional seasonal amplitude variation is 0.48 ± 0.43 times the eccentricity-induced variation which is consistent with zero. We search for solar zenith angle variations (employing the solar zenith angle as the time variable) and additional seasonal variation due to the oscillation phase (using the distance between Sun and Earth). In each bin i we calculate the rate $r_i(t)$ (oscillated Monte Carlo). From this rate and the live-time distribution the average (rate r_i^{av}), day, and night rates and subsequently the day-night asymmetry A_i are computed. Using the day (night) live times L_D (L_N) and the live-time asymmetry $L_{\text{DN}} = (L_D - L_N) / (0.5(L_D + L_N))$, the effective asymmetry

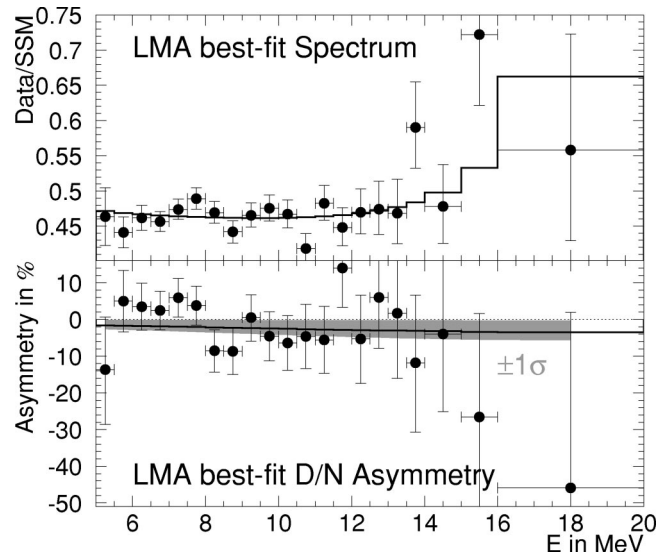


FIG. 3. LMA spectrum (top) and D/N asymmetry (bottom). The predictions (solid lines) are for $\tan^2 \theta = 0.55$ and $\Delta m^2 = 6.3 \times 10^{-5} \text{ eV}^2$ with $\phi_{8B} = 0.96 \text{ SSM}$ and $\phi_{\text{hep}} = 3.6 \text{ SSM}$. Each energy bin is fit independently to the rate (top) and the day-night asymmetry (bottom). The gray bands are the $\pm 1\sigma$ ranges corresponding to the fitted value over the entire range 5–20 MeV: $A_{\text{DN}} = -1.8 \pm 1.6\%$.

parameter $a_i = 0.25 A_i L_{\text{DN}}$ is computed and $z_i(\alpha, t)$ is defined as

$$z_i(\alpha, t) = \frac{1 + \alpha((1 + a_i)r_i(t)/r_i^{\text{av}} - 1)}{1 + \alpha \times a_i},$$

so that $r'_i(\alpha, t) = z_i(\alpha, t) \times r_i^{\text{av}}$ has the same average total rate r_i^{av} , but the day-night asymmetry is scaled to $A_i \times \alpha$. In particular, $r'_i(0, t) = r_i^{\text{av}}$ is independent of t and $r'_i(1, t) = r_i(t)$. Figure 2 shows the expected solar zenith angle variation shapes $z_i(1, \cos \theta_z)$ in five different energy bins using a LMA solution and the density model of the Earth [7].

The resulting likelihood function is maximized with respect to signal S , the backgrounds B_i , and the asymmetry scaling parameter α . For the best-fit LMA oscillation parameters (which will be described later) we find $\alpha = 0.86 \pm 0.77$ which corresponds to the day-night asymmetry

$$A_{\text{DN}} = -1.8 \pm 1.6(\text{stat})_{-1.2}^{+1.3}(\text{syst})\%$$

where -2.1% is expected for these parameters. The statistical uncertainty is reduced by 25% with this likelihood analysis, however, the resulting day-night asymmetry is still consistent with zero. Figure 3 shows the fitted rate (top), as well as the day-night asymmetry (bottom) for each energy bin separately. The oscillation expectations are indicated by the solid lines. The asymmetry fit value and uncertainty depends on the solar zenith angle variation shapes $z_i(1, t)$ which in turn depend on the oscillation parameters. Figure 4 shows the expected day-night asymmetry and fit results for each Δm^2 in the LMA region with the best-fit mixing angle $\tan^2 \theta = 0.55$. The expected day-night asymmetry and the $\pm 1\sigma$ band of the fit overlap between $(5-12) \times 10^{-5} \text{ eV}^2$.

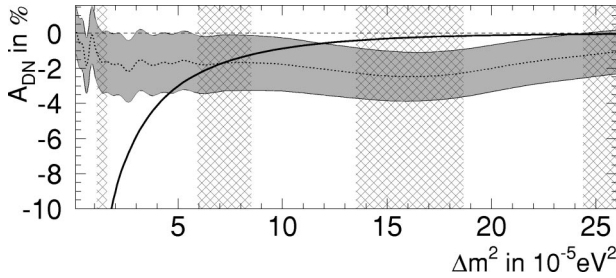


FIG. 4. SK day-night asymmetry as a function of Δm^2 . The solid line is expected from two-neutrino oscillations; the band ($\pm 1\sigma$) results from the fit to the SK data. The mixing angle $\tan^2\theta=0.55$ is used. Overlaid are the allowed ranges in Δm^2 (cross-hatched bands) from the KamLAND experiment [4]. The second band (LMA-I) is favored.

To constrain neutrino oscillation using the SK rate time variations, the likelihood difference $\Delta \log \mathcal{L} = \log \mathcal{L}(\alpha=1) - \log \mathcal{L}(\alpha=0)$ between the expected time variation and no time variation is computed. Below $\Delta m^2 \approx 2 \times 10^{-9} \text{ eV}^2$, the day-night variation is replaced by an additional seasonal variation due to the oscillation phase. As for the eccentricity-induced variation, the energy bins below 6.5 MeV are excluded from the seasonal variation, because of the time variation of the background. However, since the effect of that variation on the day-night asymmetry was carefully evaluated to be negligible, these energy bins participate in the day-night variation. To combine the time variation constraints with those from the recoil electron spectrum, $\Delta \log \mathcal{L}$ is interpreted as a time variation $\Delta \chi_{\text{tv}}^2 = -2\Delta \log \mathcal{L}$ and added to the spectrum χ^2 .

Disregarding oscillations, we calculate the interaction rates in bin i ${}^8\text{B}_i$ (hep $_i$) due to ${}^8\text{B}$ (hep) neutrinos. We also compute the oscillated rates ${}^8\text{B}_i^{\text{osc}}$ and $\text{hep}_i^{\text{osc}}$ for each $\tan^2\theta$ and Δm^2 . From these and the measured rates Data_i , we form the ratios $d_i = \text{Data}_i / ({}^8\text{B}_i + \text{hep}_i)$, $b_i = {}^8\text{B}_i^{\text{osc}} / ({}^8\text{B}_i + \text{hep}_i)$, and $h_i = \text{hep}_i^{\text{osc}} / ({}^8\text{B}_i + \text{hep}_i)$. The expected oscillation suppressions are $\beta b_i + \eta h_i$ where β (η) is the ${}^8\text{B}$ (hep) neutrino flux scaling parameter. These suppressions are modified by the correlated uncertainty distortion functions $f_i^B(\delta_B)$ (uncertainty in the ${}^8\text{B}$ neutrino spectrum), $f_i^S(\delta_S)$ (uncertainty in SK energy scale), and $f_i^R(\delta_R)$ (uncertainty in SK energy resolution) to $\rho_i = (\beta b_i + \eta h_i) / f_i$ where $f_i = f_i^B f_i^R f_i^S$. The total χ^2 is then

$$\chi^2 = \sum_{i=1}^{N_{\text{bin}}} \left(\frac{d_i - \rho_i}{\sigma_i} \right)^2 + \frac{\delta_B^2}{\sigma_B^2} + \frac{\delta_S^2}{\sigma_S^2} + \frac{\delta_R^2}{\sigma_R^2} + \Delta \chi_{\text{tv}}^2 + \left(\frac{\beta - 1}{\sigma_f} \right)^2$$

where the last term constraining the ${}^8\text{B}$ flux to the standard solar model [8] (SSM) is optional. Including this last term, the best oscillation fit is in the quasivacuum region at $\Delta m^2 = 6.49 \times 10^{-10} \text{ eV}^2$ and maximal mixing, where a summer-winter asymmetry of -0.6% is expected and $-0.3 \pm 0.7\%$ (stat) is found. The χ^2 is 17.1 for 20 degrees of freedom (65% C.L.). The LMA solution fits almost equally well: the smallest χ^2 at $\Delta m^2 = 6.3 \times 10^{-5} \text{ eV}^2$ and $\tan^2\theta = 0.55$ is

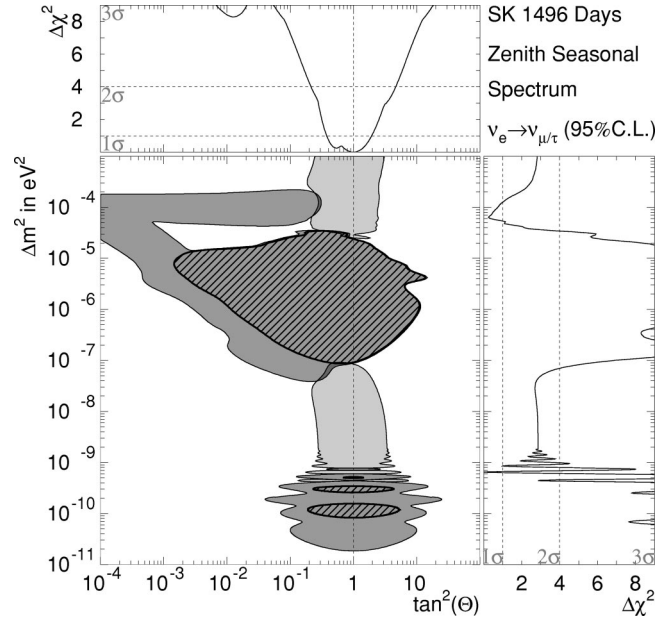


FIG. 5. Excluded (SK spectrum and time variation; dark gray) and allowed (SK spectrum, rate and time variation; light gray) at 95% C.L. Overlaid are the areas excluded just by the day-night and seasonal variation (hatched regions inside thick black lines). The graphs at the top (and right) show the χ^2 difference as a function of $\tan^2\theta$ (Δm^2) alone where the Δm^2 ($\tan^2\theta$) is chosen to minimize χ^2 .

17.3 (63% C.L.). The ${}^8\text{B}$ flux is fit to 96% SSM. The χ^2 of the SK spectrum and rate is 18.5 for 20 degrees of freedom (55% C.L.), the χ^2 to the day-night asymmetry as a function of energy (see Fig. 3) is 13.8 for 21 degrees of freedom (88% C.L.). Figure 5 shows the allowed areas at 95% C.L. using all SK information: rate, spectrum and time variation. It also shows the χ^2 as a function of $\tan^2\theta$ alone where a Δm^2 is chosen for each $\tan^2\theta$ to minimize χ^2 : SK data excludes small mixing at more than 3σ . SK data also disfavors $\Delta m^2 > 10^{-3} \text{ eV}^2$ and $2 \times 10^{-9} \text{ eV}^2 < \Delta m^2 < 3 \times 10^{-5} \text{ eV}^2$ (see the plot in the right panel, where χ^2 is minimized with respect to $\tan^2\theta$).

Stronger constraints on Δm^2 result from the combination of the SK measurements with other solar neutrino data [1]. The combined fit to SK data and the SNO measurements on the charged-current and neutral-current reactions of solar ${}^8\text{B}$ neutrinos with deuterons need not constrain any neutrino flux with a solar model. Figure 6(a) shows the allowed region at 95% C.L.: only LMA solutions survive at this confidence level. When the charged-current rates measured by Homestake, GALLEX, and SAGE are included as well, the LMA solutions are favored by 3σ , however, the fit relies on the SSM predictions of the pp, pep, CNO and ${}^7\text{Be}$ neutrino fluxes.

The first oscillation analysis of the KamLAND reactor neutrino spectrum and rate leaves several allowed areas, usually called LMA-0, LMA-I, LMA-II, and LMA-III. When we combine the analysis of SK with all other solar experiments and a binned likelihood analysis of the KamLAND data [9], the LMA-I is strongly favored over the other solutions: in

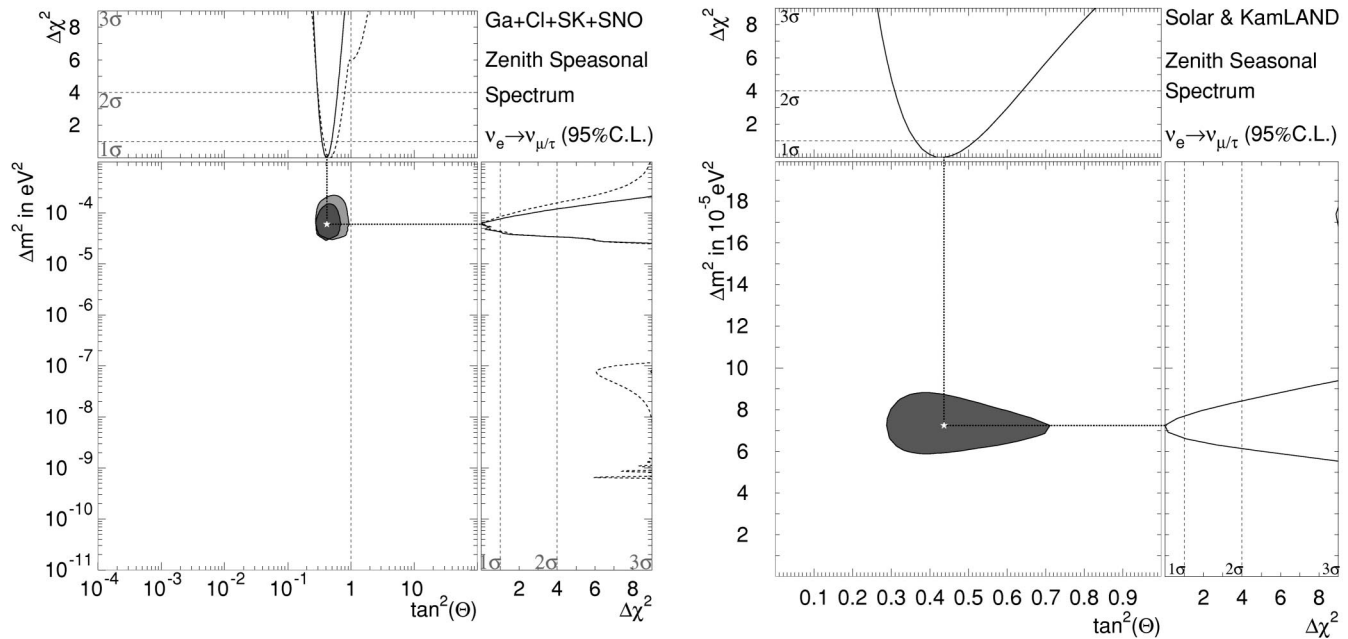


FIG. 6. (a) Allowed area at 95% C.L. from the combination of SK and SNO (gray) and all solar data (dark gray). The graphs at the top (and right) show the χ^2 difference as a function of $\tan^2\theta$ (Δm^2) only: the dashed line is the SK-SNO fit; the solid line includes all solar data. (b) Allowed area at 95% C.L. using all solar and KamLAND data. Note the linear scale of both axes. Only LMA-I remains allowed.

Fig. 6(b), the 95% allowed area is shown and the $\Delta\chi^2$ of the fit is plotted against Δm^2 (minimized with respect to $\tan^2\theta$) and $\tan^2\theta$ (minimized with respect to Δm^2).

In summary, SK has measured very precisely the ^8B neutrino flux time variations expected by two-neutrino oscillations. For the best LMA parameters, the day-night asymmetry is determined as $-1.8 \pm 1.6(\text{stat})^{+1.3}_{-1.2}(\text{syst})\%$ where -2.1% is expected. SK data disfavors large Δm^2 LMA solutions, since the expected day-night asymmetry is close to zero. In combination with other solar data and the KamLAND reactor neutrino results, the oscillation parameters are

determined as $\Delta m^2 = 7.1^{+0.6}_{-0.5} \times 10^{-5} \text{ eV}^2$ and $\tan^2\theta = 0.44 \pm 0.08$.

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