Constraints on Neutrino Oscillation Parameters from the Measurement of Day-Night Solar Neutrino Fluxes at Super-Kamiokande

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A search for day-night variations in the solar neutrino flux resulting from neutrino oscillations has been carried out using the 504 day sample of solar neutrino data obtained at Super-Kamiokande. The absence of a significant day-night variation has set an absolute flux independent exclusion region in the two neutrino oscillation parameter space. [S0031-9007(99)08599-3]

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As a real time solar neutrino experiment, Super-Kamiokande can perform a wide range of time modulation studies of the solar neutrino flux. One motivation for these types of studies is an investigation of neutrino oscillation hypotheses. All solar neutrino observations [1–5] have reported significantly lower fluxes than the expectations of standard solar models (SSMs) [6–8]. This difference is commonly referred to as the solar neutrino problem. Given the support of recent helioseismological observations [9], these SSMs look well established and reliable. The difference between observations and predictions suggests some neutrino properties beyond the standard model of elementary particles. The most popular solution to the solar neutrino problem is neutrino oscillations, aided by matter enhanced oscillations in the Sun [10]. In some regions of the parameter space for neutrino oscillations, matter enhanced oscillations within the Earth can lead to a regeneration of the measured neutrino flux passing through the Earth. This regeneration would produce a higher flux measured during nighttime relative to daytime measurements. If such a day-night variation was observed, it would be strong evidence for neutrino oscillations. The amplitude of the day-night flux variation would determine the neutrino oscillation parameters, independent of the absolute flux uncertainties of the SSMs.

Super-Kamiokande (SK) started taking data in April 1996. SK has already confirmed the deficit of solar neutrinos [5]. In this paper, the total live time is increased to 503.8 days (31 May 1996 through 25 March 1998), and the total number of solar neutrino events found coming from the Sun is now 6823^{+148}_{-130} events above a threshold of 6.5 MeV in total energy of the recoil electron. Day-night (DN) variations are investigated with this high-statistics solar neutrino data sample and an updated flux value is presented.

The SK detector is located at the Kamioka Observatory, Institute for Cosmic Ray Research, the University of Tokyo, in Gifu Prefecture, Japan, 137.32° East longitude and 36.43° North latitude. Because of the latitude, the nadir of the Sun can range between ± 0.974 in cosine (12.98° to 167.02°) at the SK site. In this analysis, nadir (θ_z) is defined as the angle between the negative z axis of the detector coordinate system and the direction to the Sun (solar neutrino direction), where the cosine of the nadir is positive when the Sun is below the horizon. Solar neutrinos will penetrate different regions of the Earth that are related to the nadir of the Sun by the following: mantle ($0 < \cos\theta_z < 0.838$), outer core ($0.838 < \cos\theta_z < 0.981$), and inner core ($0.981 < \cos\theta_z < 1$). SK never sees solar neutrinos that pass through the inner core of the Earth. However, the fact that the density of the outer core ($\sim$10–12 g/cm^3) is about double that of the mantle ($<$5.5 g/cm^3) may enhance the neutrino regeneration efficiency of the Earth. To look for effects associated with the core, the night sample was divided into five data sets according to nadir of the Sun at the time of the neutrino event, N1 ($0 < \cos\theta_z \leq 0.2$), N2 ($0.2 < \cos\theta_z \leq 0.4$), …, and N5 ($0.8 < \cos\theta_z \leq 1.0$). In the cases of N1 to N4, neutrinos pass only through the mantle of the Earth. N5 data contains the outer core-penetrating neutrino sample. In the N5 period, the Sun has spent 80% of its time in the outer core region.

The absolute energy scale of the SK detector has been calibrated precisely using a linear accelerator system (LINAC) at the detector [11]. The LINAC injects electrons downward in direction, at several fixed points in the volume and at certain times. Uniformity of the detector response in each nadir direction is important, since the data are divided according to the nadir angle. The uniformity in the azimuthal angle is also important since the nadir and azimuthal angles of the Sun are correlated. In addition, N5 data can be taken only during the winter time, so long term stability of the detector must be monitored. The precise LINAC calibration has to be extrapolated to the entire volume, in all directions, and at all times. Decay of spallation products induced by cosmic ray muons is used for this purpose. Spallation events accumulate in the data as a major background in the solar neutrino measurements ($\sim$600 events/day above 6.5 MeV threshold in a 22.5 ktons fiducial volume). They are distributed uniformly in volume, direction, and time, just as solar neutrinos. Their beta decay energy spectra are distributed in the relevant energy region for ^{8}B neutrinos, making this background a good calibration and stability monitor. The spallation event sample was divided into subsets in time and direction (nadir and azimuthal angle), and the relative energy difference was found by comparing the spectral shape of a subset with that of the whole spallation sample as a reference spectrum. The magnitude of spread of the relative energy differences is consistent with the expected statistical distribution of subsets and no systematic biases are seen in the test variables. A conservative systematic error for the relative energy scale for each N1 to N5 data set is 0.5%. Because of the steepness of the recoil electron spectrum near the analysis threshold of 6.5 MeV, this small scale error is amplified and the relative flux error of each data subset (N1–N5) in the uniformity of the energy scale is estimated to be $^{+1.2}_{-1.1}$%. Since the statistical errors of the flux values are much larger than this scale error and the spread of the relative energy scales was consistent with a statistical distribution, we treated this scale error as uncorrelated among subsets in the following analysis.

In order to be independent of the absolute flux values of ^{8}B solar neutrinos in SSMs, only the relative difference of DN flux values was used in the oscillation analysis. In this case, many of the systematic errors involving the detector response cancel. The remaining systematic errors, in addition to the relative energy scale error, are estimated to be $\pm 0.1\%$ (data reduction), $\pm 0.4\%$ (background subtraction), $\pm 0.1\%$ (live time calculation), and $<0.1\%$ (trigger efficiency) for each night subset.

Figure 1 shows the measured DN fluxes from 503.8 days of SK data. The flux is normalized to a value at one astronomical unit (AU) by a correction for the eccentricity of the Earth's orbit. Numerical values of the corrected fluxes are listed in Table I with relative systematic errors. The total flux updated for 503.8 days of data is also listed in the table with an absolute systematic error the same as was previously presented [5]. Obtained DN

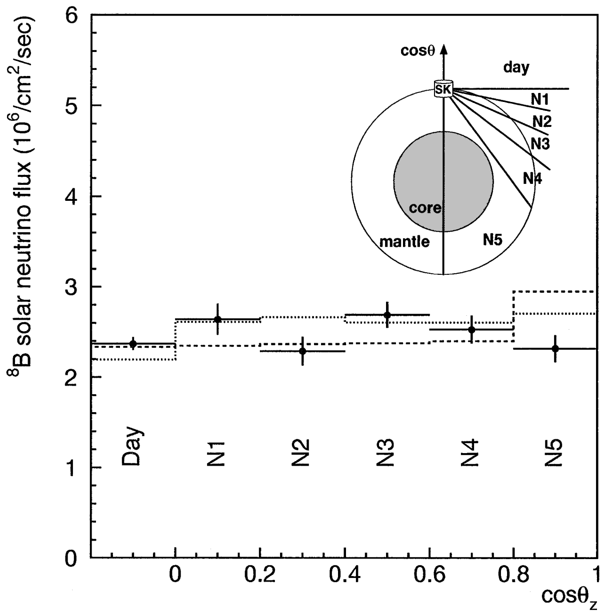

FIG. 1. Measured day/night solar neutrino fluxes as a function of the nadir of the Sun. Error bars represent statistical errors only. Night data are divided into five bins. Dotted histogram is the expected variation of a typical large angle solution and dashed histogram is that of a typical small angle solution.

asymmetries are as follows:

$$\frac{N}{D} - 1 = 0.047 \pm 0.042(\text{stat}) \pm 0.008(\text{syst}),$$

$$\frac{N5}{\langle D, N1, \ldots, N4 \rangle} - 1 = -0.055 \pm 0.063(\text{stat}) \pm 0.013(\text{syst}).$$

No significant DN variation nor N5 excess is seen in the data.

The impact of these results was investigated within a two neutrino oscillation hypothesis for $\nu_e \to \nu_\mu$ or $\nu_e \to \nu_\tau$ (active neutrinos), and $\nu_e \to \nu_s$ (sterile neutrino). A flux independent analysis was performed by treating the flux normalization factor α as a free parameter in the χ^2 definition,

$$\chi^2_{\text{DN}} = \sum_{i=D,N1,\ldots,N5} \left\{ \frac{\phi_i - \alpha \times \phi_i^{\text{osci}}(\sin^2 2\theta, \Delta m^2)}{\sqrt{\sigma_i^2 + \sigma_{\text{sys},i}^2}} \right\}^2,$$

where ϕ_i is the measured flux, and $\phi_i^{\text{osci}}(\sin^2 2\theta, \Delta m^2)$ is the effective flux for a given set of oscillation parameters derived from the ratio of the expected number of events with and without oscillations. σ_i and $\sigma_{\text{sys},i}$ are the statistical and systematic errors of the ith bin listed in Table I. The χ^2 value for the case of no oscillations is 7.4 with 5 degrees of freedom (d.o.f.), which corresponds to a 19% probability. The expected solar neutrino flux nadir dependencies for a set of oscillation parameters were obtained by a numerical calculation using models for the neutrino production point [7], electron density in the Sun [7], electron density in the Earth (PREM [12]), and ^{8}B neutrino spectrum [13]. Production points were integrated on a $0.01 R_{\text{sun}}$ grid in the plane which contains the Sun and the Earth. The electron density distribution in the Earth was calculated with charge-to-mass ratios (Z/A) of 0.468 for the core and 0.497 for the mantle [14]. Neutrino trajectories in the Earth were integrated over 1000 directions with $0.001 \cos\theta_z$ steps, weighted by SK live time. Assuming neutrino incoherence at the Earth, the electron neutrino survival probability at the detector, P_{SE}, was obtained from independent calculations of $P_{1,2}(\Delta m^2/E, \sin^2 2\theta, \mathbf{r}_0)$ and $P_{1e,2e}(\Delta m^2/E, \sin^2 2\theta, \cos\theta_z)$ using

$$P_{\text{SE}} = P_1 P_{1e} + P_2 P_{2e} = (1 - P_2)(1 - P_{2e}) + P_2 P_{2e},$$

where P_1, P_2 are the probabilities to be ν_1, ν_2 at the surface of the Sun and $\mathbf{r}_0$ is the production point of neutrinos in the Sun. P_{1e}, P_{2e} are the probabilities to be detected as a ν_e at SK if the neutrinos arrive as ν_1, ν_2, taking into account any possible regeneration in the Earth. Representative flux variations obtained from these calculations (for active neutrinos) are shown in Fig. 1 for a typical set of parameters at a large mixing angle solution ($\sin^2 2\theta = 0.56, \Delta m^2 = 1.2 \times 10^{-5}$ eV^2)

TABLE I. Day/night fluxes obtained from 503.8 days of SK data. Flux values are normalized to 1 AU. Quoted systematic error for the "all" data is an absolute error but others are relative errors.

Data set	Nadir of the Sun	Flux (10^6 cm^{-2} sec^{-1})	Syst error	Live time
Day	$-1 \leq \cos\theta_z \leq 0$	$2.369^{+0.072}_{-0.068}$(stat)	$^{+0.6}_{-0.5}$%	242.2 days
Night	$0 < \cos\theta_z \leq 1$	$2.481^{+0.068}_{-0.065}$(stat)	$^{+0.6}_{-0.5}$%	261.6 days
N1	$0 < \cos\theta_z \leq 0.2$	$2.640^{+0.170}_{-0.167}$(stat)	$^{+1.3}_{-1.2}$%	43.6 days
N2	$0.2 < \cos\theta_z \leq 0.4$	$2.289^{+0.157}_{-0.154}$(stat)	$^{+1.3}_{-1.2}$%	48.6 days
N3	$0.4 < \cos\theta_z \leq 0.6$	$2.689^{+0.144}_{-0.134}$(stat)	$^{+1.3}_{-1.2}$%	64.3 days
N4	$0.6 < \cos\theta_z \leq 0.8$	$2.526^{+0.156}_{-0.146}$(stat)	$^{+1.3}_{-1.2}$%	52.5 days
N5	$0.8 < \cos\theta_z \leq 1$	$2.318^{+0.147}_{-0.144}$(stat)	$^{+1.3}_{-1.2}$%	52.6 days
All	$-1 \leq \cos\theta_z \leq 1$	$2.436^{+0.053}_{-0.047}$(stat)$^{+0.085}_{-0.071}$(syst)		503.8 days

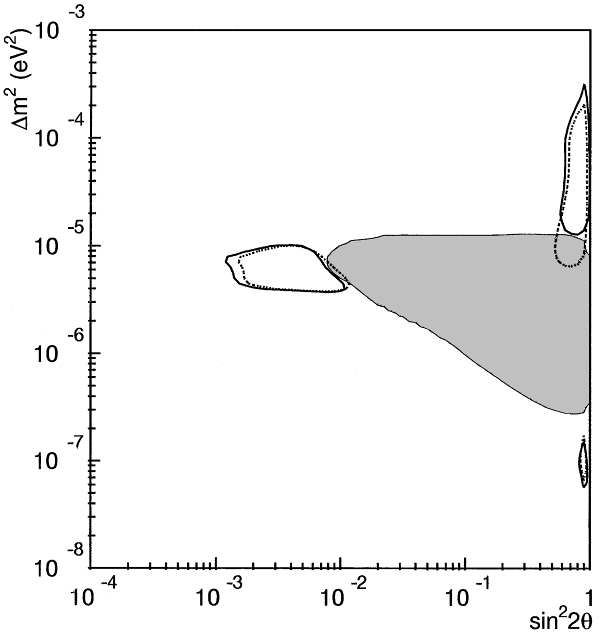

FIG. 2. Flux independent exclusion region by SK day/night variation for $\nu_e \rightarrow \nu_{\mu,\tau}$ oscillations. Exclusion probabilities larger than 99% are shown in the shaded area. Regions inside of the dotted lines are allowed at the 99% C.L. from the combined rate analysis of Homestake, SAGE, Gallex, and SK flux in comparison with the BP98 SSM [6]. Regions inside of the thick solid lines are allowed at the 99% C.L. from the combined rate analysis of the rates and the SK DN variation.

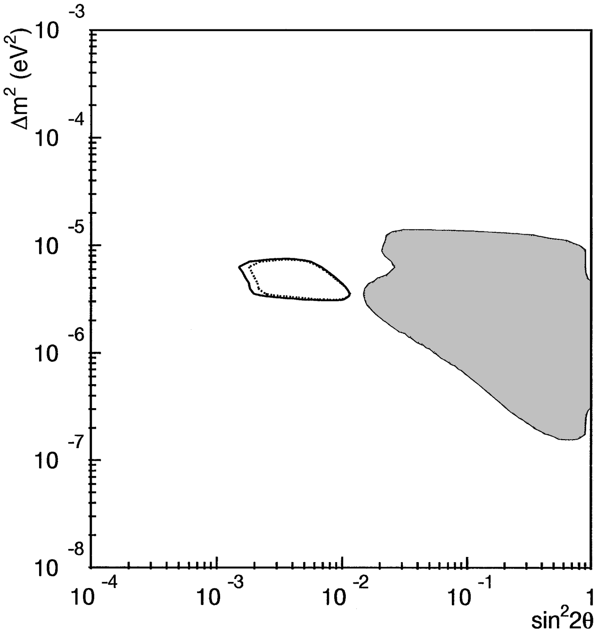

FIG. 3. Flux independent exclusion region by SK day/night variation for $\nu_e \rightarrow \nu_s$ oscillations. Regions are defined as in Fig. 2.

and for a set at a typical small mixing angle solution ($\sin^2 2\theta = 0.01, \Delta m^2 = 6.3 \times 10^{-6}$ eV^2).

The expected solar neutrino DN flux was calculated for points in the parameter space ($10^{-4} \leq \sin^2 2\theta \leq 1, 10^{-8} \leq \Delta m^2 \leq 10^{-3}$ eV^2) and compared to the measured values. Minimum χ^2 values of 5.2 were found at ($\sin^2 2\theta = 3.2 \times 10^{-2}, \Delta m^2 = 1.6 \times 10^{-6}$ eV^2) for the $\nu_e \rightarrow \nu_{\mu,\tau}$ case and 4.8 at ($\sin^2 2\theta = 0.25, \Delta m^2 = 1.8 \times 10^{-7}$ eV^2) for the $\nu_e \rightarrow \nu_s$ case. These sets of parameters cannot explain the deficits seen in the other experiments, so a hypothesis tests based on $\chi^2_{\rm DN}$ was performed to obtain an exclusion region, instead of a method based on a distance from the minimum χ^2. Figures 2 and 3 show shaded regions where the exclusion probabilities are more than 99% ($\chi^2 > 15.09$ for 5 d.o.f.), using the expected nadir dependencies for $\nu_e \rightarrow \nu_{\mu,\tau}$ and $\nu_e \rightarrow \nu_s$, respectively. The typical parameters shown in Fig. 1 are excluded. Absolute flux information was not used in these calculations so the excluded regions found are independent of the ^{8}B neutrino flux.

A combined rate analysis was performed using data from the four different solar neutrino experiments (Cl, SAGE, Gallex, and SK) with the assumption of the absolute fluxes given in [6]. The analysis follows the method given in [15] with updated theoretical uncertainties (^{37}Cl cross section [16], ^{71}Ga cross section [17], and diffusion [7]) and the latest experimental results [18]. In order to see the impact of the DN information obtained at SK, the rate analysis was performed with and without the DN information from SK. Results from this combined rate analysis are also shown in Figs. 2 and 3. Regions inside the solid and dotted lines show the allowed region at the 99% C.L. ($\chi^2 < \chi^2_{\rm min} + 9.21$) with and without DN information, respectively. In the allowed regions obtained from the rate only analysis, the χ^2 value of the DN analysis varies from 7.1 to 22.4, 6.2 to 91.3, 7.6 to 11.3, and 7.3 to 8.8 for the small angle, the large angle, and the LOW ($\Delta m^2 \sim 10^{-7}$ eV^2) solutions of $\nu_e \rightarrow \nu_{\mu,\tau}$ and the small angle solution of $\nu_e \rightarrow \nu_s$, respectively. These local minimum values are similar and the DN result doesn't discriminate these solutions with current statistics.

In summary, SK observes no DN variation in the ^{8}B solar neutrino flux in 504 days of data and sees no significant zenith angle variations. This result sets an exclusion region in the oscillation parameter space where regeneration of ν_e would be expected. That exclusion region constrains the Mikheyev-Smirnov-Wolfenstein solutions to a larger mass difference (large angle solution) or to a smaller mixing angle (small angle solution).

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[1] B. T. Cleveland *et al.,* Astrophys. J. **496**, 505 (1998).
[2] Y. Fukuda *et al.,* Phys. Rev. Lett. **77**, 1683 (1996).
[3] J. N. Abdurashitov *et al.,* Phys. Lett. B **328**, 234 (1994).
[4] P. Anselmann *et al.,* Phys. Lett. B **342**, 440 (1995); W. Hampel *et al.,* Phys. Lett. B **388**, 364 (1996).
[5] Y. Fukuda *et al.,* Phys. Rev. Lett. **81**, 1158 (1998).
[6] J. N. Bahcall, S. Basu, and M. H. Pinsonneault, Phys. Lett. B **433**, 1 (1998).
[7] J. N. Bahcall and M. Pinsonneault, Rev. Mod. Phys. **67**, 781 (1995).
[8] For example, S. Turck-Chièze and I. Lopes, Astrophys. J. **408**, 347 (1993); I.-J. Sackman *et al.,* Astrophys. J. **360**, 727 (1990); X. Shi *et al.,* Phys. Rev. D **50**, 2414 (1994); A. Dar and G. Shaviv, Astrophys. J. **468**, 933 (1996).
[9] J. N. Bahcall, M. H. Pinsonneault, S. Basu, and J. Christensen-Dalsgaard, Phys. Rev. Lett. **78**, 171 (1997).
[10] S. P. Mikheyev and A. Y. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985); L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).
[11] M. Nakahata *et al.* (to be published).
[12] A. M. Dziewonski and D. L. Anderson, Phys. Earth Planet. Inter. **25**, 297 (1981).
[13] J. N. Bahcall *et al.,* Phys. Rev. C **54**, 411 (1996).
[14] J. N. Bahcall and P. I. Krastev, Phys. Rev. C **56**, 2839 (1997).
[15] G. L. Fogli and E. Lisi, Astropart. Phys. **3**, 185 (1995).
[16] J. N. Bahcall *et al.,* Phys. Rev. C **54**, 411 (1996).
[17] J. N. Bahcall, Phys. Rev. C **56**, 3391 (1997).
[18] ^{37}Cl: $2.56 \pm 0.16 \pm 0.16$ solar neutrino units (SNU) [1]; SAGE: $66.6^{+7.8}_{-8.1}$ SNU, V. Gavrin *et al.,* in *Neutrino 98, Proceedings of the XVIII International Conference on Neutrino Physics and Astrophysics, Takayama, Japan, 1998,* edited by Y. Suzuki and Y. Totsuka (North-Holland, Amsterdam, 1999) [to be published in Nucl. Phys. B (Proc. Suppl.)]; Gallex: $77.5 \pm 6.2^{+4.3}_{-4.7}$ SNU, T. Kirsten *et al.,* in *Neutrino 98*; SK: $2.436^{+0.053+0.085}_{-0.047-0.071} \times 10^{6}$ cm^{-2} sec^{-1}, in this Letter.