First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation

A. Renshaw, K. Abe, Y. Hayato, K. Iyogi, J. Kameda, Y. Kishimoto, M. Miura, S. Moriyama, M. Nakahata, Y. Nakano, S. Nakayama, H. Sekiya, M. Shiozawa, Y. Suzuki, A. Takeda, Y. Takenaga, T. Tomura, K. Ueno, T. Yokozawa, R. A. Wendell, T. Irvine, T. Kajita, K. Kaneyuki, K. P. Lee, Y. Nishimura, K. Okumura, T. McLachlan, L. Labarga, S. Berkman, H. A. Tanaka, S. Tobayama, E. Kears, J. L. Raa, J. L. Stone, L. R. Sulak, M. Goldhaber, K. Bays, G. Carminati, W. R. Kropp, S. Mine, M. B. Suy, H. W. Sobel, K. S. Ganeev, J. Hill, W. E. Keig, N. Hong, J. Y. Kim, I. T. Lim, T. Akiri, A. Himmel, K. Scholberg, J. Hignight, A. Takeda, M. Koshiba, K. Suzuki, T. Kajita, K. Scholberg, M. Goldhabar, K. Iyogi, C. W. Walter, T. Wongjirad, T. Ishizuka, S. Tsatake, J. S. Jang, J. G. Learned, S. Matsuno, S. N. Smith, H. Asasegawa, T. Ishida, T. Ishii, T. Kobayashi, T. Nakadaira, K. Nakamura, Y. Oyama, K. Sakashita, T. Sekiguchi, T. Tsukamoto, A. T. Suzuki, Y. Takeuchi, C. Bronner, S. Hirota, K. Nakaya, K. Suzuki, S. Takahashi, Y. Fukuda, K. Choi, Y. Ito, G. Mitsuka, P. Mijakowski, J. Hignight, J. Imber, C. K. Jung, Y. Yanagisawa, H. Ishino, A. Kiyoshi, T. Morii, M. Sakuda, T. Yano, Y. Kuno, R. Tacik, S. B. Kim, H. Okazawa, Y. Choi, K. Nishijima, M. Koshiba, Y. Totsuka, M. Yokoyama, M. Martens, Ll. Marti, M. R. Vagins, J. F. Martin, P. de Perio, A. Konaka, M. J. Wilking, S. Chen, Y. Zhang, and R. J. Wilkes (The Super-Kamiokande Collaboration)

1 Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo, Kamioka, Gifu 506-1205, Japan
2 Research Center for Cosmic Neutrinos, Institute for Cosmic Ray Research, University of Tokyo, Kamioka, Chiba 277-8582, Japan
3 Department of Theoretical Physics, University Autonoma Madrid, 28049 Madrid, Spain
4 Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, V6T1Z4, Canada
5 Department of Physics, Boston University, Boston, MA 02215, USA
6 Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
7 Department of Physics and Astronomy, University of California, Irvine, Irvine, CA 92697-4575, USA
8 Department of Physics, California State University, Dominguez Hills, Carson, CA 90747, USA
9 Department of Physics, Chonnam National University, Kwangju 500-757, Korea
10 Department of Physics, Duke University, Durham NC 27708, USA
11 Junior College, Fukuoka Institute of Technology, Fukuoka, Fukuoka 811-0295, Japan
12 Department of Physics, Gifu University, Gifu, Gifu 501-1193, Japan
13 GIST College, Gwangju Institute of Science and Technology, Gwangju 500-712, Korea
14 Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA
15 High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
16 Department of Physics, Kobe University, Kobe 657-8501, Japan
17 Department of Physics, Kyoto University, Kyoto 606-8502, Japan
18 Department of Physics, Miyagi University of Education, Sendai, Miyagi 980-0845, Japan
19 Solar Terrestrial Environment Laboratory, Nagoya University, Nagoya, Aichi 464-8600, Japan
20 Department of Physics and Astronomy, State University of New York at Stony Brook, NY 11794-3800, USA
21 Department of Physics, Okayama University, Okayama, Okayama 700-8530, Japan
22 Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
23 Department of Physics, University of Regina, 3737 Wascana Parkway, Regina, SK, S4S0A2, Canada
24 Department of Physics, Seoul National University, Seoul 151-742, Korea
25 Department of Informatics in Social Welfare, Shizuoka University of Welfare, Yaizu, Shizuoka, 425-8611, Japan
26 Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea
27 Department of Physics, Tokai University, Hiratsuka, Kanagawa 259-1292, Japan
28 The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan
29 Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, University of Tokyo, Kashiwa, Chiba 277-8582, Japan
30 Department of Physics, University of Toronto, 60 St. Toronto, Ontario, M5S1A7, Canada
31 Institute of Particle Physics, Canada, University of Toronto, 60 Saint George St., Toronto, ON, M5S1A7, Canada
32 TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T2A3, Canada
33 Department of Engineering Physics, Tsinghua University, Beijing, 100084, China
34 Department of Physics, University of Washington, Seattle, WA 98195-1560, USA
35 National Centre For Nuclear Research, 00-681 Warsaw, Poland

(Dated: March 25, 2014)
We report an indication that the elastic scattering rate of solar $^8$B neutrinos with electrons in the Super-Kamiokande detector is larger when the neutrinos pass through the Earth during nighttime. We determine the day/night asymmetry, defined as the difference of the average day rate and average night rate divided by the average of those two rates, to be $(−3.2 ± 1.1(\text{stat}) ± 0.5(\text{syst}))\%$, which deviates from zero by 2.7 $\sigma$. Since the elastic scattering process is mostly sensitive to electron-flavored solar neutrinos, a non-zero day/night asymmetry implies that the flavor oscillations of solar neutrinos are affected by the presence of matter within the neutrinos’ flight path. Super-Kamiokande’s day/night asymmetry is consistent with neutrino oscillations for $4 × 10^{-5}$ eV$^2$, and large mixing values of $\theta_{12}$, at the 68% C.L.

Neutrino flavor oscillations occur when the phase difference of a superposition of massive neutrinos changes. Such phase changes occur while neutrinos are propagating in vacuum (vacuum oscillations). Wolfenstein [1] realized that the neutrino-electron elastic forward-scattering amplitude introduces additional phase shifts. As a consequence, neutrinos propagating in matter will oscillate differently than neutrinos propagating through vacuum. These matter effects are a fundamental prediction of the present theory of neutrino oscillations. In this letter, we report an indication of the existence of such matter effects.

Vacuum oscillations cannot easily explain a solar neutrino electron-flavor survival probability $P_{ee}$, which is measured to be significantly below one half [2, 3], in the energy region of ~8 to 18 MeV. Mikheyev and Smirnov [5] explained this experimental fact as the adiabatic transformation of the neutrinos through the varying solar density causing a resonant conversion to the second mass eigenstate inside the Sun (MSW resonance). Lower energy (<2 MeV) solar neutrino data [10] are still described well as averaged vacuum oscillations. However, searches for the transition of $P_{ee}$ from the MSW resonance to vacuum oscillations (near 3 MeV) were so far unsuccessful [8, 11]. Moreover, these previous observations imply matter effects only indirectly, since there is no “control beam” of solar neutrinos that only propagates in vacuum. Atmospheric neutrino experiments can probe the existence of matter effects within the Earth in a similar fashion, and while there is currently no significant departure of present atmospheric data [12, 13] from the vacuum oscillation predictions, these effects will serve to determine the mass hierarchy and CP phase in future atmospheric and long baseline experiments.

The cleanest and most direct test of matter effects on neutrino oscillations is the comparison of the daytime and the nighttime solar neutrino interaction rates (solar day/night effect). In this comparison, the solar zenith angle controls the size and length of the terrestrial matter density through which the neutrinos pass, and thereby the oscillation probability and the observed interaction rate. An increase in the nighttime interaction rates implies a regeneration of electron-flavor neutrinos. Other solar neutrino measurements [2, 3, 14] have found no significant day/night differences. Here, we report a 2.7 $\sigma$ indication of a non-zero solar neutrino day/night effect [1].

Super-Kamiokande (SK) is a 50,000 metric ton cylindrical water Cherenkov detector. The optically separated 32,000 ton inner detector (ID), viewed by ~11,100 50 cm diameter photomultiplier tubes (PMTs), is surrounded by an 18,000 ton active veto shield, viewed by ~1,900 20 cm diameter PMTs. The detector is described in detail in [15]. SK detects recoil electrons coming from the elastic scattering of solar neutrinos with electrons. Only $^8$B and $\text{hep}$ solar neutrinos produce recoil electrons of sufficiently high energy to be detected in SK. Neutrino-electron elastic scattering is mostly sensitive to electron-flavored neutrinos, because the cross section for the elastic scattering of solar neutrinos with electrons is six times smaller, since only the electron-neutrino day/night effect. The scattering vertex is reconstructed using the timing of the Cherenkov light, while the direction and energy of the recoil electrons are determined from the light pattern and intensity. For 10 MeV electrons in SK-IV, the vertex resolution is 52 cm, the directional resolution is 25° (limited by multiple Coulomb scattering), and the energy resolution is 14.0% (dominated by Poisson fluctuations of the number of photons detected with ~6 photo-electrons per MeV). More details are given in [4–6, 11].

There are four distinct phases of SK. Initially, SK-I had 11,146 ID PMTs and used 1,496 live days between 1996 and 2001 for low-energy analysis [4]. In 2001, an accident during maintenance destroyed ~7,000 ID PMTs. 5,182 surviving and spare ID PMTs were then deployed for SK-II [5], running between 2002–2005, with a total low-energy analysis livetime of 791 days. After full reconstruction of the detector, SK-III [6] took data between 2005 and 2008, acquiring 548 live days for the low-energy analysis, with 11,129 ID PMTs. Since 2008, SK-IV has been running with upgraded electronics and data acquisition system (DAQ). In this paper, data from SK-I, SK-II, SK-III and 1,306 live days of SK-IV are used [11]. The day/night analysis uses recoil electrons above 4.5 MeV in SK-I, III, and IV and 7 MeV in SK-II. The energy range of the SK-I-III day/night analysis is identical as in [4, 6]; however, here it is quoted as kinetic energy (we simply
subtracted 0.5 MeV) while [4-6] use total energy. In [11], the observed solar neutrino signal at lower recoil electron energies is used for the flux and spectrum analysis.

At the time of each event, the solar zenith angle $\theta_z$ is determined. This is the angle between the vector from the solar position to the event vertex and the vertical detector ($z$) axis. The precision of this angle is much better than $10^{-3}$, the bin width used in the following analysis. The accuracy of this angle is limited only by SK’s absolute time precision (a few 100 ns) and basic astronomy. The SK elastic scattering rate as a function of the solar zenith angle $r(\cos \theta_z)$ is used to search for a day/night difference in the interaction rate. The expected change in the interaction rate due to the varying Sun-Earth distance (induced by the eccentricity of Earth’s orbit) is taken into account throughout this paper. The most straightforward method to look for a day/night effect is to define separate day ($\cos \theta_z \leq 0$) and night ($\cos \theta_z > 0$) samples. Based on $r_D$ ($r_N$), the average scattering rate of the day (night) sample, we define the SK day/night asymmetry as $A_{DN} = (r_D - r_N)/\frac{1}{2}(r_D + r_N)$. Therefore, $A_{DN} = 0$ implies no terrestrial matter effect on solar neutrino oscillations.

To increase sensitivity, [16] first introduced an unbinned maximum likelihood fit of the solar zenith angle distribution of the rate $r(\cos \theta_z)$ to the day/night variation amplitude $\alpha$. This was done using “shapes” of such variations expected from neutrino oscillation calculations. By construction, $\alpha$ scales the calculated day/night asymmetry $A_{DN}^{\text{calc}}$ while leaving the average rate unchanged, giving the measured day/night asymmetry $A_{DN} = A_{DN}^{\text{calc}} \times \alpha$. This more sophisticated method, referred to as the “amplitude fit”, was also used in [4]. The calculated oscillation shapes ignore the SK daytime overburden, which can be up to a few kilometers depending on the solar zenith angle.

We refer to the angle between the solar and reconstructed recoil electron candidate directions as $\theta_{\text{sun}}$. The solar neutrino interaction rate is extracted by an extended maximum likelihood fit [4] to the $\cos \theta_{\text{sun}}$ distribution. [16] expands the signal likelihood to allow for a time-dependent solar neutrino-electron elastic scattering rate, parameterized by the amplitude scaling variable $\alpha$. The best-fit $\alpha$, multiplied with $A_{DN}^{\text{calc}}$, defines a best-fit $A_{DN}^{\text{fit}}$. In this manner the day/night asymmetry is measured more precisely statistically. It is also less vulnerable to some key systematic effects, such as directional variation of the energy scale (the frequency of which is limited by SK’s angular resolution, $\sim 25^\circ$).

Because the amplitude fit depends on the shape of the day/night variation, given for each energy bin in [16] (and also in [4]), it necessarily depends on the assumed oscillation parameters. Vacuum oscillations depend on the neutrino energy, the length of the flight path $L$ and the oscillation parameters; the difference of the squared masses of the mass eigenstates $\Delta m_{ij}^2$ ($i = 1, 2, 3, \ldots$) and the mixing of the mass eigenstates with the flavor eigenstates (mixing angles $\theta_{ij}$). If the neutrinos propagate through matter, then the density of the matter will effectively change the oscillation parameters. It was shown analytically by [17-19] that $r(\cos \theta_z) - r_D$ oscillates with the vacuum frequency $\frac{\Delta m_{21}^2}{2E}L$, if $L \approx 2R \cos \theta_z$ denotes now the path length of the neutrino inside the Earth ($R$ being the Earth radius). Although the dependence of matter effects on the mixing angles (in or near the large mixing angle solutions and for $\theta_{13}$ values consistent with reactor neutrino measurements [20]) is quite small, the dependence on $\Delta m_{21}^2$ is more noticeable. The fit is run for solar oscillation parameter sets which predict various matter effects ($10^{-9}$ eV$^2 \leq \Delta m_{21}^2 \leq 10^{-3}$ eV$^2$ and $10^{-4} \leq \sin^2 \theta_{12} \leq 1$), for values of $\sin^2 \theta_{13}$ between 0.015 and 0.035.

Fig. 1 combines the data from all four SK phases to show the measured zenith angle distribution of the flux assuming no oscillations. The expected zenith variation assuming best-fit oscillation parameters [11] from a global fit based on solar neutrino data [2-4, 8-10, 11] is overlaid in solid red. The dashed blue line also includes reactor anti-neutrino data [22]. The day and night flux values given in the left portion of Fig. 1 imply a day/night asymmetry of $A_{DN} = (-4.2 \pm 1.2 \text{(stat)})\%$. The ninth data point in the right panel of Fig. 1 shows an $\sim 2$ sigma deviation, enhancing the resulting $A_{DN}$. We believe this is a statistical fluctuation, accounted for by the quoted statistical uncertainties. The result $A_{DN}^{\text{fit}}$ coming from the unbinned maximum likelihood fit is less prone to these types of fluctuations. To calculate the total systematic uncertainty, the individual systematic uncertainties

\[ A_{DN}^{\text{fit}} = \frac{1}{2}(A_{DN}^{\text{calc}} \times \alpha) \]

\[ \alpha = \frac{r_D - r_N}{r_D + r_N} \]

\[ r_D = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \]

\[ r_N = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \]

\[ A_{DN}^{\text{calc}} = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \times \cos \theta_{\text{sun}} \]

\[ A_{DN}^{\text{fit}} = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \times \cos \theta_{\text{sun}} \times \alpha \]

\[ \alpha = \frac{r_D - r_N}{r_D + r_N} \]

\[ r_D = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \]

\[ r_N = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \]

\[ A_{DN}^{\text{calc}} = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \times \cos \theta_{\text{sun}} \]

\[ A_{DN}^{\text{fit}} = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \times \cos \theta_{\text{sun}} \times \alpha \]

\[ \alpha = \frac{r_D - r_N}{r_D + r_N} \]

\[ r_D = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \]

\[ r_N = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \]

\[ A_{DN}^{\text{calc}} = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \times \cos \theta_{\text{sun}} \]

\[ A_{DN}^{\text{fit}} = \frac{1}{2} \sum \text{events} \times \text{efficiency} \times \frac{1}{\text{bin width}} \times \cos \theta_{\text{sun}} \times \alpha \]
TABLE I. Day/night asymmetry for each SK phase, coming from separate day and night rate measurements (middle column) and the amplitude fit (right column). The uncertainties shown are statistical and systematic. The entire right column assumes the SK best-fit point of oscillation parameters.

| SK phase | Day/Night Asymmetry (%) |
|----------|----------------------------|
| SK-I     | (−2.1 ± 2.0 ± 1.3)%       |
| SK-II    | (−5.5 ± 4.2 ± 3.7)%       |
| SK-III   | (−5.9 ± 3.2 ± 1.3)%       |
| SK-IV    | (−5.3 ± 2.0 ± 1.4)%       |
| Combined | (−4.2 ± 1.2 ± 0.8)%       |

TABLE II. Day/night amplitude fit systematic uncertainties by SK phase. The total is found by adding the contributions for each phase in quadrature.

| SK phase | Energy Scale | Energy Resolution | Background Shape | Event Selection | Earth Model | Total |
|----------|--------------|-------------------|------------------|----------------|-------------|-------|
| SK-I     | 0.8%         | 0.5%              | 0.2%             | —              | 0.01%       | 1.0%  |
| SK-II    | 0.3%         | 0.05%             | 0.6%             | 0.2%           | 0.01%       | 1.0%  |
| SK-III   | 0.2%         | 0.6%              | 0.6%             | 0.6%           | 0.01%       | 0.7%  |
| SK-IV    | 0.05%        | 0.05%             | 0.05%            | 0.1%           | 0.01%       | 0.6%  |
| Combined | 1.0%         | 1.0%              | 0.7%             | 0.6%           |             |       |

FIG. 2. SK day/night amplitude fit as a function of recoil electron kinetic energy (unlike [16] which uses total energy), shown as the measured amplitude times the expected day/night asymmetry, for oscillation parameters chosen by the SK best-fit. The error bars shown are statistical uncertainties only and the expected dependence is shown in red.

soratively assigned to be the same as that of the simple day/night asymmetry measurement (see [4, 5]). Because [4, 5] only give total systematic uncertainties and not those for each of the components, we have now re-estimated the systematic uncertainties of the day/night amplitude fit of the first two SK phases, using similar methods as for SK-III and IV. The methods for estimating the systematic uncertainties of the amplitude fit in SK-III and IV are detailed in [11] (see Section 9.3). A summary of the various components of the systematic uncertainty on the day/night amplitude fit, as well as the total, is given in Table II for each SK phase.

During the SK-I and II phases, the largest contribution to the systematic uncertainty comes from the directional dependence of the energy scale. From the beginning of the SK-III phase, a depth-dependent water transparency parameter was introduced into the MC simulation program. This corrects for the depth-dependence of the water absorption coefficient and greatly reduces the directional dependence of the energy scale. The further reduction seen from SK-III to SK-IV comes from an improvement in the comparison between data and MC timing, the result of the electronics upgrade prior to SK-IV. The largest contribution to the systematic uncertainty now comes from the expected background shapes, which are derived from fits to the detector’s zenith and azimuthal angle distributions after statistical subtraction of the solar neutrinos. The accuracy of these shapes are limited by statistics.

The additional contribution to the systematic uncertainty during SK-III and IV, coming from the event selection, is the result of the combination of the external...
event and tight fiducial volume cuts (see [6, 11]). The tight fiducial volume cut introduced at the start of SK-III is asymmetric in the $z$ direction, causing the external event cut to have different selection efficiencies during the day and night times. As for the case of the simple day/night asymmetry measurement, the total systematic uncertainty of each SK phase is assumed to be uncorrelated, and is added in quadrature to the statistical uncertainty of the corresponding phase before combining the results of each phase together.

The right column of Table I lists the measured day/night asymmetry coming from the amplitude fit to each phase, as well as the combined fit, for oscillation parameters at the SK best-fit point. The combined fit takes into account energy threshold and resolution. The equivalent SK day/night asymmetry coming from the amplitude fit is

$$A_{\text{DN}}^{\text{fit}} = (-3.2 \pm 1.1 \text{(stat)} \pm 0.5 \text{(syst)})\%,$$

which differs from zero by 2.7 $\sigma$. The measured value of the day/night asymmetry agrees with $-3.2\%$, within $\pm 0.2\%$, for all sets of oscillation parameters contained in the large mixing angle region. The SNO experiment also performed a search for the day/night variation of the charged-current interaction rate on deuterium [8]. We scale the expected coefficients (based on $\Delta m_{21}^2$) by an amplitude of the day/night asymmetry, another handle to minimize the SNO probability as $\alpha$.

Fig. 3 shows the dependence of the measured day/night asymmetry (fitted day/night amplitude times the expected day/night asymmetry (red)) on $\Delta m_{21}^2$, for $\sin^2 \theta_{12} = 0.314$ and $\sin^2 \theta_{13} = 0.025$. The 1 $\sigma$ statistical uncertainties are given by the light gray band. The additional dark gray width to the band shows the inclusion of the systematic uncertainties. Overlaid are the 1 $\sigma$ allowed ranges from the solar global fit (solid green) and the KamLAND experiment (dashed blue).

In conclusion, we find an indication of electron-flavor regeneration in solar neutrino oscillations due to the presence of several oscillation parameters: $\Delta m_{21}^2$ is the day/night variation frequency. Although the amplitude of the day/night variation is too small (compared to present uncertainties) to measure the frequency, some frequencies are favored by about 2 $\sigma$ over others.

Even so, the neutrino flux-independent solar neutrino oscillation analysis of [16] uses frequency and amplitude of the day/night variation as well as spectral information. We calculate the log likelihood ratio between $\alpha = 1$ and $\alpha = 0$, multiply by $-2$, and then add it to the $\chi^2$ values of the fit to the recoil electron spectrum (see [11]). Fig. 4 shows the flux-independent SK-I/II/III/IV contours of 68% (solid thin line), 95% (solid thick line), three sigma (dashed-dotted line), and five sigma (dashed gray line) significance. For the 95% C.L., regions preferred by the day/night variation data are highlighted in gray. In the case of 68% C.L., those regions closely match the two lower $\Delta m_{21}^2$ 68% contours shown in the figure. The black asterisk marks the parameters selected by all solar neutrino [8, 11, 11, 23] and KamLAND data [22], including this work. The SK flux-independent contours agree with those parameters within two sigma. The previously suggested low (small mixing angle) solution of neutrino oscillation parameters is excluded at more than four (five) sigmas.

\[2\] SNO actually models the night/day asymmetry of the survival probability as $a_0 + a_1 (E_{\nu} - 10 \text{ MeV})$ and fits the coefficients $a_1$ [8]. We scale the expected coefficients (based on $\Delta m_{21}^2 = 4.84 \times 10^{-5} \text{eV}^2$) by an amplitude $a_{\text{SNO}}$ and minimize the SNO $\chi^2$ with respect to it. SNO data then implies $a_0 = (3.4 \pm 2.9)\%$, while SK and SNO combined is equivalent to $a_0 = (4.8 \pm 1.6)\%$.

\[3\] The Low and small mixing angle solution parameters can be seen in [8] and [23], respectively.
ence of terrestrial matter effects. The fit amplitude of the solar zenith angle variation of the SK solar neutrino interaction rate corresponds to a day/night asymmetry of \((-3.2 \pm 1.1\) (stat) \(\pm 0.5\) (syst))%, which deviates from zero by 2.7 \(\sigma\). This analysis probes matter effects directly, since it compares the flavor content of the solar neutrino beam with Earth matter to that without. Therefore, this is the first direct indication that neutrino oscillation probabilities are modified by the presence of matter.

The authors gratefully acknowledge the cooperation of the Kamioka Mining and Smelting Company. Super-K has been built and operated from funds provided by the Japanese Ministry of Education, Culture, Sports, Science and Technology, the U.S. Department of Energy, and the U.S. National Science Foundation. This work was partially supported by the Research Foundation of Korea (BK21 and KNRC), the Korean Ministry of Science and Technology, the National Science Foundation of China (Grant NO. 11235006), the European Union FP7 ITN INVISIBLES (Marie Curie Actions, PITN-GA-2011-289442) and the State Committee for Scientific Research in Poland.

FIG. 4. Contours at 68% (solid thin line), 95% (solid thick line), three sigma (dashed-dotted line), and five sigma (dashed gray line) of the flux-independent SK solar neutrino oscillation analysis. The shaded gray area indicates regions preferred by the day/night variation data for the 95% case. The best-fit parameters resulting from a fit to all solar neutrino [8, 10, 11, 23] and KamLAND [22] data is shown by the black asterisk.

\[ \Delta m_{21}^2 = 2.7 \times 10^{-5} \text{ eV}^2 \]

\[ \tan^2(2 \theta_{12}) = 0.38 \]

\[ (1\text{stat}) \pm 0.5 \text{syst})\% \]

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