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Search for Day-Night and Semiannual Variations in the Solar Neutrino Flux Observed in the Kamiokande-II Detector

K. S. Hirata, K. Inoue, T. Kajita, K. Kihara, M. Nakahata, K. Nakamura, S. Ohara, N. Sato,[a]
Y. Suzuki, Y. Totsuka, and Y. Yaginuma
Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan

M. Mori, Y. Oyama, A. Suzuki, K. Takahashi, and M. Yamada
National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan

M. Koshiba and K. Nishijima
Tokai University, Shibuya, Tokyo 151, Japan

T. Suda and T. Tajima
Department of Physics, Kobe University, Kobe, Hyogo 657, Japan

K. Miyano, H. Miyata, and H. Takei
Niigata University, Niigata, Niigata 950-21, Japan

Y. Fukuda, E. Kodera, Y. Nagashima, and M. Takita
Department of Physics, Osaka University, Toyonaka, Osaka 560, Japan

K. Kaneyuki and T. Tanimori
Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152, Japan

E. W. Beier, L. R. Feldscher, E. D. Frank, W. Frati, S. B. Kim,[b] A. K. Mann, F. M. Newcomer,
R. Van Berg, and W. Zhang[c]
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
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Searches for possible day-night and semiannual variations of the ^{8}B solar neutrino flux are reported based on 1040 days of Kamiokande-II data. Within statistical error, no such short-time variations were observed. The limit on the day-night difference sets a constraint on neutrino-oscillation parameters. A region defined by $\sin^2 2\theta \gtrsim 0.02$ and $2\times10^{-6} \lesssim \Delta m^2 \lesssim 10^{-5}$ eV^2 is excluded at 90% C.L. without any assumption on the absolute value of the expected solar neutrino flux.

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Neutrino signals from ^{8}B decay in the Sun have been observed in the Kamiokande-II (KAM-II) detector.[1,2] The flux value obtained is 0.46 ± 0.05(stat) ±0.06(syst) relative to the standard-solar-model (SSM) calculation of Bahcall and Ulrich,[3] and 0.70 ± 0.08(stat) ±0.09(syst) relative to the calculation of Turck-Chièze *et al.*[4] The KAM-II result, together with the result of the ^{37}Cl detector,[5] shows a "deficit" of solar neutrinos which has been called the solar neutrino problem. Various solutions for that problem have been proposed. Among them are unknown errors in the input parameters of the SSM calculations, new properties of neutrinos such as neutrino mass and mixing or a neutrino magnetic moment, and exotic massive particles at the core of the Sun. In particular, neutrino oscillations, which depend on nonzero neutrino mass and mixing, especially the Mikheyev-Smirnov-Wolfenstein[6] (MSW) effect, must be considered seriously since that effect naturally explains the results of both the ^{37}Cl and KAM-II detectors, and the preliminary result of the SAGE (^{71}Ga) detector.[7]

Terrestrial regeneration of ν_e through the MSW effect may give rise to a small difference between the daytime and night-time solar neutrino fluxes, and also to a small seasonal variation in the observed flux.[8] In addition, if the neutrino has a magnetic moment of the order of $10^{-10}\mu_B$ (where μ_B is the Bohr magneton), the solar neutrino flux might also vary semiannually (as opposed to seasonally) because of a possible difference in the solar magnetic field traversed by neutrinos reaching the Earth.[9] If a day-night difference or semiannual variation were to be observed, the solar neutrino deficit could then be ascribed to neutrino oscillations or to a magnetic moment without reference to the quantitative predictions of the solar neutrino fluxes of the SSM. In this Letter we report the results of a search for short-time variations in the ^{8}B solar neutrino flux. Based on those results, an additional constraint[10] on neutrino-oscillation parameters is obtained.

KAM-II detects recoil electrons from neutrino-electron scattering. Details of the detector have been described elsewhere.[11] The analysis reported here is based on 1040 days of data taken from January 1987 through April 1990; for the first 450 days (January 1987 through May 1988) the electron (total) energy threshold used in the analysis is 9.3 MeV, while for the remaining 590 days the threshold is taken to be 7.5 MeV.

The data were divided into daytime and night-time samples, where the daytime (night-time) sample is taken while the Sun is above (below) the horizon. The effective data-taking times are 500 and 540 equivalent days for the daytime and night-time samples, respectively. The solar neutrino flux for each sample is measured by fitting the observed electron angular distribution with an isotropic background plus an expected angular distribution relative to the Sun.[1,2] The fluxes so obtained are $0.91 \pm 0.15(\text{stat})$ for daytime and $1.07 \pm 0.16(\text{stat})$ for night-time relative to the averaged value. These are shown as circles in Fig. 1(a). The relative difference between the daytime and night-time fluxes is expressed by

$$\frac{\text{day}-\text{night}}{\text{day}+\text{night}} = -0.08 \pm 0.11(\text{stat}) \pm 0.03(\text{syst}) ,$$

where the systematic error will be discussed below. The total data sample was also divided into four samples corresponding to the four seasons and the measured fluxes for them are shown in Fig. 1(b). The time interval for each season is 4 February–5 May, 6 May–4 August, 5 August–3 November, and 4 November–3 February for spring, summer, fall, and winter, respectively. A correction for the small variation ($\lesssim 6\%$) of the flux induced by the eccentricity of the Earth's orbit was made. Within statistical errors, there is no significant difference between the daytime and night-time fluxes, nor any seasonal variation.

A semiannual variation of the solar neutrino flux is possible because the solar equatorial plane and the ecliptic plane cross with an opening angle of 7°15′ twice per year. A line from the Earth to the center of the Sun crosses the equatorial plane around 7 June and 8 December. At these times, the detector views the core of the Sun through the solar equator, where the magnetic field is expected to be weaker than at a higher solar latitude. The strength of the interaction of a neutrino magnetic moment with the solar magnetic field would be less at those times and consequently a maximum modulation of the solar neutrino flux might occur.

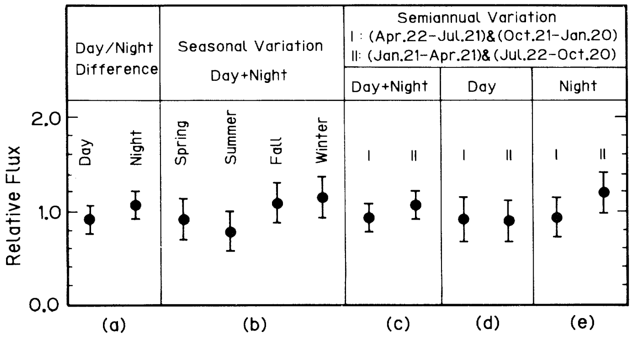

FIG. 1. Measured solar neutrino fluxes relative to the averaged value: (a) daytime, night-time; (b) spring, summer, fall, winter; (c) periods I and II; (d) periods I and II, daytime; (e) periods I and II, night-time.

To search for this effect the year was divided into two periods: period I, 22 April–21 July and 21 October–20 January and period II, 21 January–21 April and 22 July–20 October. Period I (II) corresponds to the time interval in which the Earth is near (far from) the intersection of the ecliptic plane with the solar equatorial plane. The solar neutrino fluxes during these periods were obtained as described above, and the results are $0.94 \pm 0.16(\text{stat})$ and $1.06 \pm 0.15(\text{stat})$ relative to the averaged value for periods I and II, respectively, as is shown in Fig. 1(c). Thus, the relative difference is expressed by

$$\frac{\text{period I}-\text{period II}}{\text{period I}+\text{period II}} = -0.06 \pm 0.11(\text{stat}) \pm 0.02(\text{syst}) .$$

To study the effect further, more restricted time intervals were selected. The fluxes from one-month time periods around the times when the Earth is nearest and farthest from the intersection are $0.71 \pm 0.27(\text{stat})$ and $1.12 \pm 0.26(\text{stat})$, respectively. These results do not indicate a significant anticorrelation with the strength of the magnetic field, and consequently contain no evidence for a magnetic interaction of ν_e in the Sun.

A day-night difference would at some level be correlated with a semiannual variation, because the day and night durations vary with the time of year. Accordingly, we searched for a semiannual variation using the day and night samples separately to distinguish any day-night effect from any semiannual variation. The resultant fluxes are shown in Figs. 1(d) and 1(e), which confirm the negative result in Fig. 1(c), and justify using the total data sample to extract the implication of the null day-night result for the MSW effect.

Any day-night difference or seasonal variation induced by regeneration in the Earth of ν_e that have been converted, say, to ν_μ by the MSW effect in the Sun would depend on the different path lengths and density profiles experienced by the neutrinos passing through the Earth. More information on neutrino oscillations can be extracted from the solar neutrino data by dividing the total sample into subsamples with different paths through the Earth. The path length (and density profiles) has a one-to-one correspondence with the angle of the Sun relative to the detector coordinate system, e.g., the angle δ_{Sun} between the radius vector from the Sun and the z axis of the detector. (Here, $\delta_{\text{Sun}}=0$ corresponds to the direction in which the Sun is just below the detector.)

Hence, we divided the data into six subsamples based on $\cos\delta_{\mathrm{Sun}}$, which are $\cos\delta_{\mathrm{Sun}} < 0$ (daytime sample), and $\cos\delta_{\mathrm{Sun}} = 0$–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and 0.8–1.0. The data-taking time for each subsample was 500, 92, 103, 137, 113, and 99 equivalent days, respectively. The fluxes obtained from the data subsamples are shown in Fig. 2. The reduced χ^2 calculated under the assumption of constant flux with respect to $\cos\delta_{\mathrm{Sun}}$ is 0.43 for five degrees of freedom, which corresponds to an 83% C.L.

In the neutrino-oscillation analysis only the relative flux values are used, and it was necessary to estimate carefully possible systematic errors in the relative values. A possible time variation of the gain of the detector has a negligible effect because it affects equally all $\cos\delta_{\mathrm{Sun}}$ data subsamples. A more probable source of systematic error is a possible small anisotropy in the $\cos\delta_{\mathrm{Sun}}$ distribution of the background in each of the relatively low-statistics subsamples with respect to the direction of the Sun. This possible error was estimated by studying the directional correlation of the background in each $\cos\delta_{\mathrm{Sun}}$ interval. Any systematic error from this cause is estimated to be less than 8% of the observed signal in that interval, which is much less than the statistical error in that interval.

To connect the results in Figs. 1 and 2 with the MSW parameters, the propagation of neutrinos through the Sun and the Earth was calculated numerically as follows.[12] The Schrödinger equation for neutrino propagation from the center to the surface of the Sun was solved. The distance from the Sun to the Earth varies due to the eccentricity of the Earth's orbit. This variation is much larger than the vacuum oscillation length $4\pi E_\nu/\Delta m^2$ for $10^{-6} \lesssim \Delta m^2 \lesssim 10^{-5}$ eV^2 suggested by the totality of the solar neutrino data.[10,13] As a consequence, the calculation of neutrino propagation between the Sun and the Earth can be simplified by choosing initial wave functions which correspond to the random phases of neutrinos reaching the Earth. The probability $P(\nu_e \rightarrow \nu_e)$ that ν_e remains as ν_e was obtained by averaging the results from the different initial wave functions. The density distributions in the Sun and the Earth were taken from the SSM (Ref. 3) and from geophysical calculations.[14] Recoil-electron spectra were obtained by convoluting the energy spectrum of the ^{8}B solar neutrinos with the calculated $P(\nu_e \rightarrow \nu_e)$. The contribution from $\nu_\mu e$ (or $\nu_\tau e$) scattering, with cross section $\sim \frac{1}{7}$ that of $\nu_e e$ scattering, was included, as was the energy resolution of the detector. Last, the flux in each $\cos\delta_{\mathrm{Sun}}$ interval, averaged over energy, was calculated.

Comparison of data and theory was performed with a standard χ^2 function defined by

$$\chi^2 = \sum_{\cos\delta_{\mathrm{Sun}}} \frac{[F_{\mathrm{obs}}(\cos\delta_{\mathrm{Sun}}) - xF_{\mathrm{osc}}(\cos\delta_{\mathrm{Sun}})]^2}{\sigma_F^2},$$

where $F_{\mathrm{obs}}(\cos\delta_{\mathrm{Sun}})$ and $F_{\mathrm{osc}}(\cos\delta_{\mathrm{Sun}})$ are the observed and calculated fluxes, the latter for each pair of oscillation parameters, Δm^2 and $\sin^2 2\theta$, and σ_F is the experimental error (quadratic sum of statistical and systematic errors) in the observed fluxes. The quantity x is the scale factor which is varied to a reach a minimum χ^2. Note that this procedure exploits the null time dependence of the observed flux, and does not rely directly on the absolute value of the predicted flux.

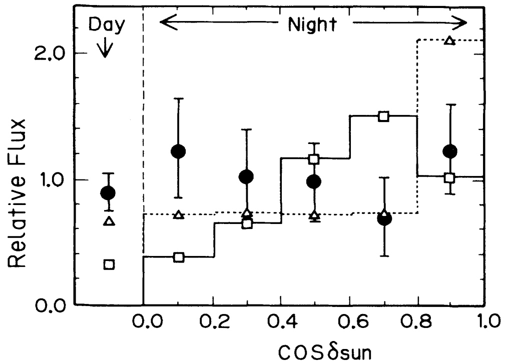

FIG. 2. Measured solar neutrino fluxes of daytime and subdivided night-time relative to the averaged value (solid circles). The horizontal axis ($\cos\delta_{\mathrm{Sun}}$) is the cosine of the zenith angle of the Sun relative to the z axis of the detector. $\delta_{\mathrm{Sun}} = 0$ corresponds to the direction in which the Sun is just below the detector. The solid-line histogram with open squares is the flux calculated for $\Delta m^2 = 3.5 \times 10^{-6}$ eV^2 and $\sin^2 2\theta = 0.11$; the dashed-line histogram with open triangles is for $\Delta m^2 = 7.9 \times 10^{-6}$ eV^2 and $\sin^2 2\theta = 0.05$.

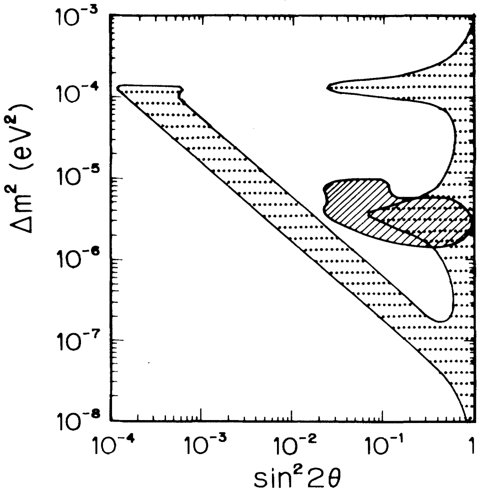

FIG. 3. Region excluded at 90% C.L. in the MSW Δm^2-$\sin^2 2\theta$ space by the null day-night result (crosshatched region). The dotted region shows the 90%-confidence-level contour for the "allowed" region which was obtained from the total flux and the recoil-electron energy spectrum, measured in the KAM-II detector.

The $\cos\delta_{\mathrm{Sun}}$ dependence of the solar neutrino flux for two pairs of oscillation parameters $[xF_{\mathrm{osc}}(\cos\delta_{\mathrm{Sun}})]$ is shown as the histograms in Fig. 2 to illustrate the nature of the results of the calculation. The minimum χ^2 (χ^2_{min}) occurs at $\sin^2 2\theta = 0.13$ and $\Delta m^2 = 1.3\times10^{-5}$ eV^2 with the value of 1.20 for three degrees of freedom. The region $\chi^2 > \chi^2_{\mathrm{min}} + 4.61$ is *excluded* with 90% confidence by the analysis of the day-night effect alone, and is shown by the crosshatched region in Fig. 3. The previously *allowed* region in the MSW parameter space which was obtained from KAM-II measurements of the total flux and the recoil-electron energy spectrum[10] is shown by the dotted region in Fig. 3.

In conclusion, the KAM-II solar neutrino data do not show day-night nor semiannual variations. Using the result of the day-night difference, the parameter region of $\sin^2 2\theta \gtrsim 0.02$ and $\Delta m^2 = (2\times10^{-6}) - 10^{-5}$ eV^2 is excluded at 90% C.L. without any assumption on the absolute value of the expected solar neutrino flux.

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[a] Now at National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan.

[b] Now at The University of Michigan, Ann Arbor, MI 48109.

[c] Now at Los Alamos National Laboratory, Los Alamos, NM 87545.

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