Constraints on Neutrino-Oscillation Parameters from the Kamiokande-II Solar-Neutrino Data

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An analysis of the Mikheyev-Smirnov-Wolfenstein effect using 1040 days of Kamiokande-II data is reported, which provides constraints on neutrino-oscillation parameters. The measured recoil-electron energy spectrum alone leads to the conclusion that the adiabatic region, $7.2\times10^{-4} < \sin^2 2\theta < 6.3\times10^{-3}$, $\Delta m^2 \sim 1.3\times10^{-4}$ (eV)^2, is disfavored at the 90% confidence level.

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A real-time, directional solar-neutrino signal has been observed in the water Cherenkov detector, Kamiokande-II (KAM-II).[1,2] The flux value obtained is 0.46 ± 0.05(stat)±0.6(syst) relative to the standard solar model (SSM) of Bahcall and Ulrich,[3] and 0.70 ± 0.08(stat)±0.09(syst) relative to a similar calculation by Turck-Chieze *et al.*[4] The difference between the predicted values and the KAM-II and ^{37}Cl-detector experimental values (the KAM-II result is approximately 60% larger than the 20-yr average flux value determined by the ^{37}Cl detector[5]) has been thought to be related to the incompleteness of the SSM or to as yet undiscovered properties of neutrinos.

Indications that the observed neutrino flux obtained by the ^{37}Cl experiment might exhibit an anticorrelation with sunspot activity brought attention to possible electromagnetic properties of neutrinos in an attempt to explain the deficit and the apparent time variation of the solar-neutrino flux.[5,6] In Ref. 2, however, no time variation is observed within experimental errors from 1040 days of KAM-II data during which the sunspot activity changed by a factor of approximately 15. It is therefore natural to consider the original idea of Mikheyev, Smirnov, and Wolfenstein (MSW),[7,8] relating to the possibility of enhanced neutrino oscillations in matter, in the light of the total data sample of KAM-II.

The KAM-II detector, in which neutrino-electron scattering is utilized in the detection of low-energy solar neutrinos, has several advantages over radiochemical detectors such as ^{37}Cl and ^{71}Ga experiments. Specifically, the ability to measure the differential recoil-electron energy spectrum (hereafter it is simply called electron spectrum) with a relatively low threshold of 7.5 MeV is useful because it provides a constraint on oscillation parameters in addition to the constraint imposed by the total flux. The electron spectrum is sensitive to the original neutrino spectrum. In the framework of the MSW effect, high-energy neutrinos (ν_e) are suppressed (converted) in the large-Δm^2, small-mixing-angle solutions (adiabatic), and low-energy neutrinos are converted and high-energy neutrinos partially suppressed in the nonadiabatic solutions, while the shape of the neutrino spectrum is basically unchanged from the expected shape if the deficit is due to a problem with the SSM.

Attempts to obtain the MSW solutions for the existent solar-neutrino data have been made by many authors.[9-12] In the most recent analysis,[11] the information of the electron spectrum was not fully implemented, but used only as a weighting factor to obtain the effective total flux by integration.

In this Letter we report on the results of an MSW analysis using 1040 days of KAM-II data, for the time period of January 1987 through April 1990. The electron spectrum shape is utilized to obtain the MSW solutions. Exact numerical integration is employed for calculating the electron-neutrino survival probability through the Sun, and no approximate analytic expressions are used. Also, two-flavor oscillations are assumed, and regeneration through the Earth which affects the large-mixing-angle region near $\Delta m^2 \sim 10^{-6}$ (eV)^2 is neglected.

Expected neutrino spectra at the location of the KAM-II detector, altered through the matter-enhanced neutrino oscillations, were calculated for neutrino oscillation parameters ($\sin^2 2\theta$, Δm^2). The area specified by $10^{-4} < \sin^2 2\theta < 1$ and $10^4 < E/\Delta m^2 < 10^9$ MeV/(eV)^2 was first divided into 41×251 grids. For each point on the grid, the electron-neutrino survival probability was calculated by numerical integration through the solar interior for which the solar density distribution of Table X in Ref. 3 was used. For the adiabatic region in which $E/\Delta m^2 \sim 10^5$ MeV/(eV)^2, the spatial distribution of the production points in the Sun was taken from the Table IX in Ref. 3, because the level crossing occurs near the solar core and the solution is somewhat sensitive to the production point. Then the neutrino spectrum for each point in the $\sin^2 2\theta$-Δm^2 plane (41×51 grids) was obtained by sorting those results according to the solar spectrum.

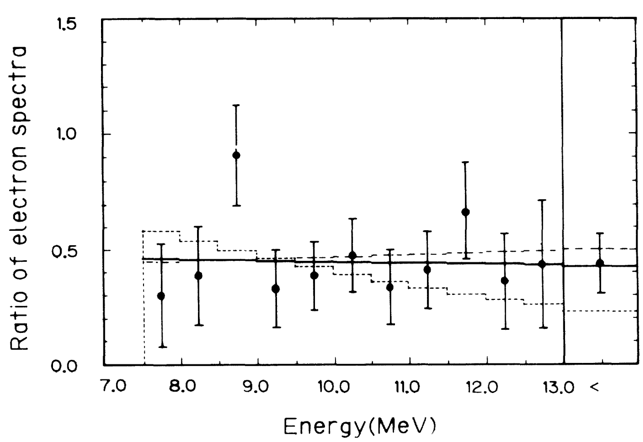

FIG. 1. The points are the ratio of the KAM-II differential recoil-electron energy spectrum to the expected spectrum (see text) as a function of the observed recoil-electron energy. The lines are the distorted electron spectra due to neutrino oscillations with representative parameters ($\sin^2 2\theta$, Δm^2): (6.3×10^{-1}, 10^{-4}) for the solid line, (10^{-2}, 3.2×10^{-6}) for the dash-dotted line, and (2×10^{-3}, 1.4×10^{-4}) for the dashed line.

A Gaussian resolution function for the energy response of the detector was used to calculate the electron spectra from the above obtained neutrino fluxes. A result obtained by using the resolution function was compared with the result from a full detector simulator, which was used in the real data analysis, and the agreement was quite satisfactory. Note that the data used in the analysis are essentially divided into two subsamples with different experimental conditions: one for 450 days of data obtained before the gain doubling of the photomultiplier tubes and the other for 590 days of data taken after that.[2] Two different calculations were performed for them. The different detector responses and the different thresholds were properly taken into account.

The ratio of the observed differential electron spectrum to the expected distribution in the absence of oscillations is plotted as a function of recoil-electron energy in Fig. 1. The shape of the expected (Monte Carlo calculated) distribution depends only on the known β-decay spectrum of ^{8}B, the cross section for the reaction $\nu_e e \to \nu_e e$, and the measured energy resolution and calibration of the detector. Shown also are three curves, representing neutrino oscillations with typical parameter ($\sin^2 2\theta$, Δm^2) values. In Fig. 1 the higher-energy bins above 13 MeV are combined to avoid bins with very small statistics. Figure 1 indicates that the energy spectrum is important in helping to discriminate among MSW solutions. The distribution of the data points in Fig. 1 is consistent with being flat at 70% C.L. ($\chi^2_{\rm red} = 0.74$). Accordingly the MSW solution with $\Delta m^2 \sim 1.4\times10^{-4}$ and $\sin^2 2\theta = 2\times10^{-3}$ (dashed line) is less favored than the two other solutions shown in Fig. 1.

Three different fits to yield quantitative information on the MSW solutions from KAM-II data were carried out. The flux value of the SSM (hereafter the SSM flux), 5.8×10^6 cm^{-2}sec^{-1}, for the ^{8}B total flux was taken for the first two fits.

(a) The total flux only was used in the fit. A systematic error of 0.06 on the measured flux[2] was folded in. The confidence contours are shown in Fig. 2(a) at the 68% (hatched), 90% (solid line), and 95% (dashed line) levels of the "allowed" parameter regions.

(b) Both the energy spectrum and total flux were used in the fit. A χ^2 was determined for the measured and calculated electron spectra in Fig. 1. The χ^2 was defined as

$$\chi^2 = \sum \frac{(x_i - \alpha x_{0i})^2}{\sigma_i^2} + \left(\frac{\alpha - 1}{\sigma_\alpha}\right)^2, \qquad (1)$$

where i runs over electron-energy bins, x_i is the observed ratio, x_{0i} is the expected ratio from a given neutrino oscillation, σ_i is the statistical error in each bin, and α is

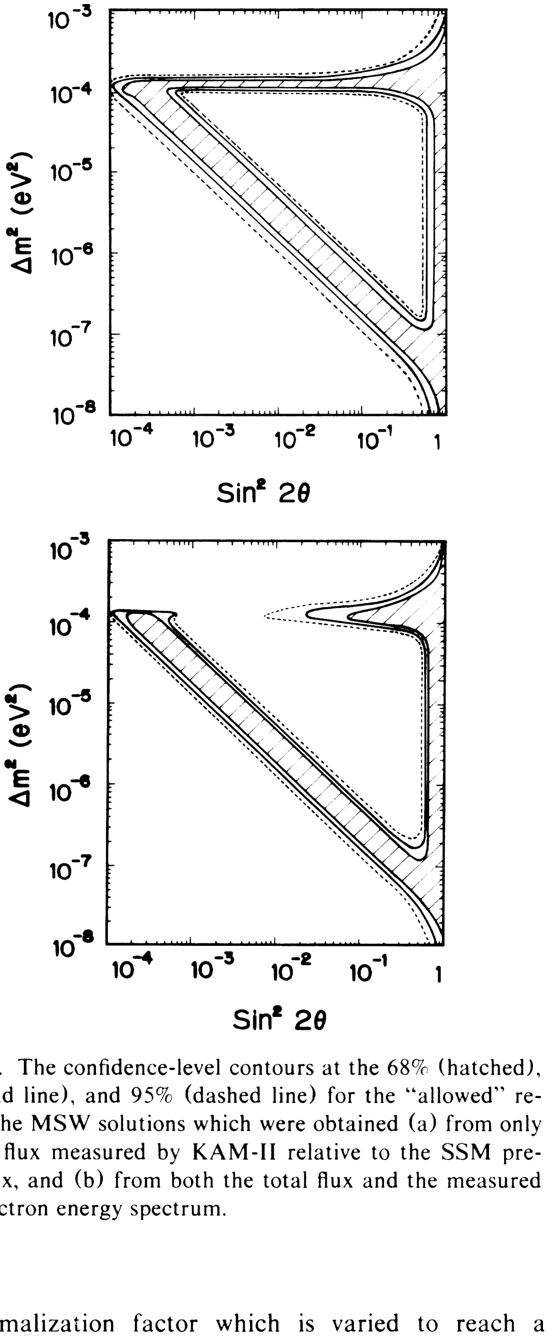

FIG. 2. The confidence-level contours at the 68% (hatched), 90% (solid line), and 95% (dashed line) for the "allowed" regions of the MSW solutions which were obtained (a) from only the total flux measured by KAM-II relative to the SSM predicted flux, and (b) from both the total flux and the measured recoil-electron energy spectrum.

the normalization factor which is varied to reach a minimum χ^2 within the constraint of the systematic error of σ_α. The confidence contours at the 68%, 90%, and 95% levels for the allowed regions are shown in Fig. 2(b). The electron spectrum in conjunction with the total neutrino flux imposes an additional constraint on the neutrino-oscillation parameters. The adiabatic solution with $6.3\times10^{-4}<\sin^2 2\theta<2.2\times10^{-2}$ is disfavored at the 90% C.L. in Fig. 2(b) which, it should be emphasized, uses only KAM-II data.

(c) A χ^2 fit without the constraint of the normalization (total flux) was performed to see the effectiveness of the electron spectrum more clearly. In practice the second term in formula (1) was removed and α in the

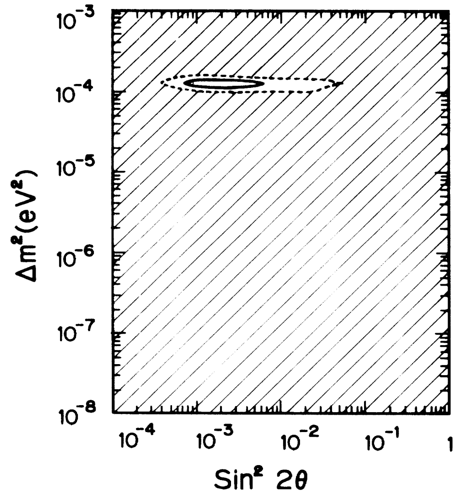

FIG. 3. The "excluded" region estimated from the recoil-electron energy spectrum alone. These contours show the 68% (dashed) and 90% (solid) confidence levels for the excluded regions. The hatched region shows the "allowed region." This excluded region is obtained from the relative shape of the energy spectrum and does not depend on the absolute flux value predicted by the SSM.

first term was treated as a free parameter. In Fig. 3 the region shown around $\Delta m^2 \sim 1.3\times10^{-4}$ $(\mathrm{eV})^2$ is the "excluded" region at 68% (dashed line) and 90% (solid line) C.L. The result in Fig. 3 shows that much of the adiabatic region is rejected by the spectrum shape alone. This excluded region is free from the normalization of both the data and the SSM.

Special care has been taken to check the biases which might affect the results of the electron-spectrum-shape fits. For example, the overall energy scale was shifted by $\pm 3\%$,[1] and the energy scale was shifted by $\pm 3\%$ in one of the two subsamples noted above which were then combined. Other similar tests were performed, but none made a noticeable difference in the confidence contours.

In summary, the solar-neutrino data from the KAM-II detector have been analyzed for compatibility with the different solutions in the MSW formalism. The measured recoil-electron energy spectrum alone disfavors the region of the adiabatic solution, $\Delta m^2 \sim 1.3\times10^{-4}$ $(\mathrm{eV})^2$, $7.2\times10^{-4}<\sin^2 2\theta<6.3\times10^{-3}$ at 90% C.L.

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