Results from One Thousand Days of Real-Time, Directional Solar-Neutrino Data

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(Received 5 June 1990)

A data sample of 1040 days from the Kamiokande II detector, consisting of subsamples of 450 days at electron-energy threshold $E_e \gtrsim 9.3$ MeV and 590 days at $E_e \gtrsim 7.5$ MeV, yields a clear directional correlation of the solar-neutrino-induced electron events with respect to the Sun and a measurement of the differential electron-energy distribution. These provide unequivocal evidence for the production of ^{8}B by fusion in the Sun. The measured flux of ^{8}B solar neutrinos from the two subsamples relative to a prediction of the standard solar model is $0.46 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$. The total data sample is tested for short-term time variation; within the statistical error, no significant variation is observed.

PACS numbers: 96.60.Kx, 95.85.Qx, 96.40.Tv

A primary motivation of the study of solar neutrinos is the prospect that it will directly reveal the inner structure of the Sun. At the same time, it may also reveal as yet undetected intrinsic properties of neutrinos, owing to the wide range of matter density, the very long distance from the Sun to the Earth, and the relatively high magnetic field traversed by low-energy solar neutrinos in their passage from the center of the Sun to a detector on Earth.

In a previous paper,[1] we describe the observation of ^{8}B solar neutrinos during an exposure of 450 live days of the detector Kamiokande II in the time period January 1987 through May 1988. The principal result of that observation was a measurement of the value of the ^{8}B solar-neutrino flux relative to that predicted by the standard solar model (SSM),[2] to wit, $0.46 \pm 0.13(\text{stat}) \pm 0.08(\text{syst})$, for observed recoil-electron total energies of $E_e \gtrsim 9.3$ MeV. The neutrino signal was correlated with the direction from the Sun, and the shape of the differential total-energy spectrum was consistent with that predicted from the product of the ^{8}B decay spectrum[3] and the cross section $\sigma(\nu_e e \rightarrow \nu_e e)$, which is the reaction for detecting low-energy ν_e in Kamiokande II.

Here we report the data from an additional 590 live detector days in the period June 1988 through April 1990, obtained with a lower background level due to improved detector performance and reduction of the radioisotopes (primarily ^{222}Rn) present in the detector water. These improvements permitted a lower electron-energy threshold of 7.5 MeV to be used. The data so obtained, in conjunction with the earlier 450-day data sample, are of particular interest, because they extend over a 1040-day period in which the sunspot activity[4] has risen steeply from a minimum value at the end of solar magnetic cycle 21 to a maximum value approximately 15 times larger at the present peak of solar cycle 22. Accordingly, it is possible to test for a correlation of the B solar-neutrino yield with the sunspot activity[5] by comparing the ^{8}B flux value obtained from the later sample with that from the earlier sample and by further subdividing the total data sample into five time intervals, each of approximately 200 live detector days. We also present the resultant relative flux value and differential electron-energy distribution from the combined samples.

The tests described here bear on the possible influence of the solar magnetic field on the ^{8}B solar-neutrino flux;[6] they are essentially empirical and do not rely on quantitative comparison with theory. In particular, the absolute value of the ^{8}B solar-neutrino flux predicted by the SSM is not necessary for these tests.

The Kamiokande II detector has been described previously,[7] as has the method of extracting the solar-neutrino signal from the data.[1,8] In June 1988, however, the gain of the photomultiplier tubes (PMT) was increased by a factor of 2 to improve the single-photoelectron response of the detector. The effect of the PMT-gain increase was to increase the number of hit PMT at a given energy, thus obtaining better event reconstruction as well as improved energy resolution. The energy-resolution improvement is summarized quantitatively by the fact that the gain change, 30 hit (effective[7]) PMT correspond to 10 MeV, whereas before the gain change, the ratio was 26 hit (effective) PMT per 10 MeV. In addition, successful efforts to seal the system of the main detector tank and water circulation equipment against the abundant radon in the mine air resulted in a lower radon content in the system and, therefore, a lower raw trigger rate. Together, the modifications led to a detector trigger threshold of 6.1 MeV with 50% efficiency, and an electron-energy threshold in the analysis of 7.5 MeV. The analysis was also improved to further reduce the background,[9] though the method is essentially the same as before.[1] The previous 450-day data were accordingly reanalyzed, and the resultant flux value was consistent with the value already published[1] with a statistical error improved by 30%.

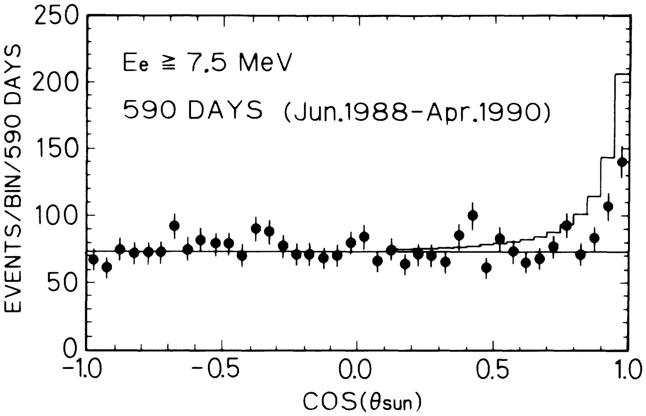

FIG. 1. Distribution in $\cos\theta_{\rm Sun}$ of the 590-day sample for $E_e \geq 7.5$ MeV. $\theta_{\rm Sun}$ is the angle between the momentum vector of an electron observed at a given time and the direction from the Sun relative to the detector at that time. The isotropic background (roughly 0.1 event/daybin) is due to spallation products induced by cosmic-ray muons, γ rays from outside the detector, and radioactivity in the detector water. The histogram is the calculated signal distribution based on the full value of the SSM and includes multiple scattering and the angular resolution of the detector.

Two independent analyses were performed on the data. Each analysis obtained the final sample using totally independent programs for event reconstruction and applying different cuts. The results of the two analyses were carefully compared in many ways after each cut. The agreement between the two analyses on the measured signal and the distributions shown below is excellent.

Figure 1 shows the distribution in $\cos\theta_{\rm Sun}$ with $E_e \geq 7.5$ MeV of the 590 days of data taken in the period June 1988 through April 1990. The number of events in the broad peak at $\cos\theta_{\rm Sun}=1$ is 164, giving a signal-to-background ratio of approximately 0.5 in the signal region ($\cos\theta_{\rm Sun} \gtrsim 0.8$). The resultant value of the ratio data/SSM from the sample in Fig. 1 is 0.45 ± 0.06(stat) ± 0.06(syst). The statistical error is significantly smaller than that given for the earlier, 450-day sample because of the lower-electron-energy threshold and the later lower background level described above. The systematic error is also reduced by the improved analysis and energy resolution. Sources of the systematic error are uncertainties in energy calibration (0.053), in angular resolution (0.031), and in dead time of various cuts (0.014). The overall systematic error is thus $[(0.053)^2+(0.031)^2+(0.014)^2]^{1/2}=0.06$.

We plot in Fig. 2 the ratio data/"SSM" as a function of time. We emphasize that the relative positions of the five data points in Fig. 2 do not depend on an absolute value of the ^{8}B flux predicted by the SSM. (We use

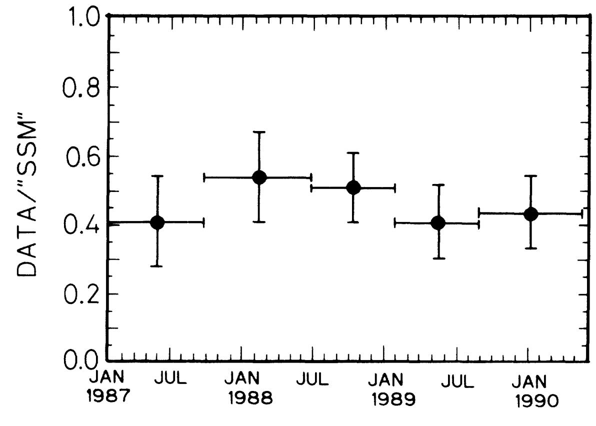

FIG. 2. Plot showing the time variation of the ^{8}B solar-neutrino signal in the Kamiokande II detector. Threshold for the two earlier points is $E_e \geq 9.3$ MeV, while for the three later points $E_e \geq 7.5$ MeV.

"SSM" to remind the reader of that fact.) Nor are those points subject to a significant systematic error arising from the aforementioned gain change because the Monte Carlo calculation that yields the value in the denominator of the ratio data/"SSM" has applied to it the same event criteria as applied to the observed events which enter the numerator. Accordingly, a difference in the energy scales before and after the gain change tends to cancel in the ratio data/"SSM". Furthermore, the distribution in Fig. 2 is not appreciably changed if a common energy threshold, e.g., $E_e \geq 9.3$ MeV, is used for all data, which additionally reduces any effect arising from different energy thresholds in the two data samples. The point-to-point systematic error is estimated using γ rays from $\mathrm{Ni}(n,\gamma)\mathrm{Ni}$ reactions and spallation products induced by cosmic-ray muons and it is within ±8%.

The $\cos\theta_{\mathrm{Sun}}$ distribution of the combined 1040-day data sample for $E_e \geq 9.3$ MeV is shown in Fig. 3. (The choice of $E_e \geq 9.3$ MeV allows the two samples to be combined directly into a single $\cos\theta_{\mathrm{Sun}}$ distribution.) The signal in the peak near $\cos\theta_{\mathrm{Sun}} = 1$ is 128 events, yielding a signal-to-background ratio of approximately 0.9 in that region. The statistical significance of the directional correlation of the solar-neutrino signal with respect to the Sun is excellent: 36% C.L. for an isotropic distribution plus a peak versus $2\times10^{-4}\%$ C.L. for an isotropic distribution only, where the Kolmogorov-Smirnov test was used in the calculation of the C.L. The peak is characterized such that the peak width and height are determined by the experimental angular resolution and the measured total flux value, respectively.

The energy distribution of the scattered electrons from the 1040-day sample is given in Fig. 4. The points in Fig. 4 were obtained by a maximum-likelihood fit to each $\cos\theta_{\mathrm{Sun}}$ distribution corresponding to a given electron-energy bin with the fits involving an isotropic background plus an expected angular distribution of the signal. The $\cos\theta_{\mathrm{Sun}}$ distribution of each energy bin shows clear enhancement in the direction of the Sun. The shape of the energy spectrum in Fig. 4 is different from that of the background; the probability that the signal and background shapes are the same is less than 3%. Above $E_e = 7.5$ MeV, the shape of the distribution is seen to be consistent with the shape of the Monte Carlo distribution based on the known β-decay spectrum of ^{8}B, the cross section for the reaction $\nu_e e \rightarrow \nu_e e$, and the measured energy resolution and calibration of the detector.

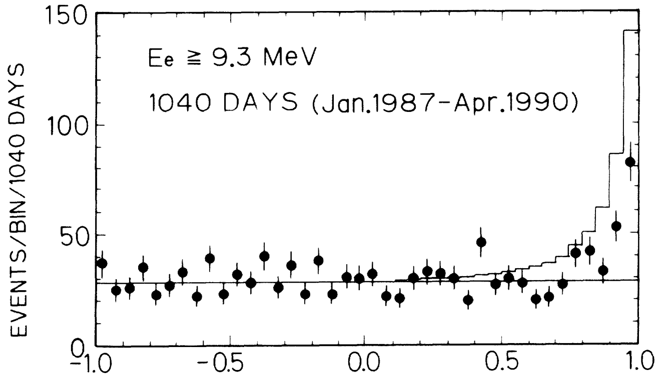

FIG. 3. Distribution in $\cos\theta_{\mathrm{Sun}}$ of the combined 1040-day sample for $E_e \geq 9.3$ MeV. The value of the ratio data/SSM from this figure is 0.43 ± 0.06.

The representative flux value for the combined 450- and 590-day data samples is

$$\mathrm{data/SSM} = 0.46 \pm 0.05(\mathrm{stat}) \pm 0.06(\mathrm{syst}).$$

In summary, there is no significant difference between the relative flux values of the 450- and 590-day data samples, which are $0.48 \pm 0.09(\mathrm{stat}) \pm 0.08(\mathrm{syst})$ ($E_e \geq 9.3$ MeV; January 1987-May 1988),[9] and $0.45 \pm 0.06(\mathrm{stat}) \pm 0.06(\mathrm{syst})$ ($E_e \geq 7.5$ MeV; June 1988-April 1990), respectively, essentially independent of electron-energy threshold. The finer-binned time-variation plot in Fig. 2 is also consistent statistically with a flux of ^{8}B solar neutrinos constant in time, but a possible time variation related to sunspot activity cannot be definitively ruled out by these data.

The totality of the ^{8}B solar-neutrino data from Kamiokande II provides a clear two-part evidence for a neutrino signal from ^{8}B production and decay in the Sun: namely, the directional correlation of the neutrino signal with the Sun, and the consistency of the differential electron-energy distribution of the signal in

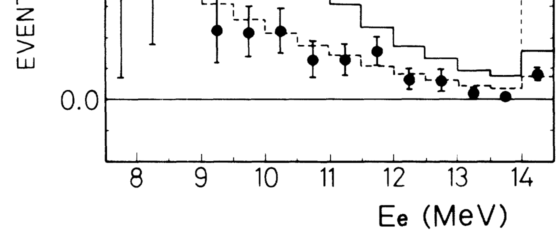

FIG. 4. Differential energy distribution of the recoil electrons from $\nu_e e \rightarrow \nu_e e$ from the 1040-day sample. The last bin corresponds to $E_e = 14$–20 MeV. The solid histogram shows the area and the shape of the distribution predicted by the SSM. The dashed histogram is the best fit ($0.46\times$SSM) of the expected Monte Carlo-calculated distribution to the data.

shape and energy scale with that expected from ^{8}B decay. Accordingly, the mechanism of energy generation in the Sun based on the fusion reactions which give rise to ^{8}B as a by-product would appear to be unequivocally confirmed by the detection of neutrinos which could only have originated in the core of the Sun.

We gratefully acknowledge the cooperation of the Kamioka Mining and Smelting Company. We thank K. Arisaka and B. G. Cortez for their contributions to the early stage of this experiment. This work was supported by the Japanese Ministry of Education, Science and Culture, by the U.S. Department of Energy, and by the University of Pennsylvania Research Fund. Part of this analysis was carried out on the FACOM M780 and M380 at the computer facilities of the Institute for Nuclear Study, University of Tokyo, and part at the David Rittenhouse Computing Facility of the University of Pennsylvania.

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