Solar Neutrino Data Covering Solar Cycle 22

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(Received 4 March 1996)

Results from 1036 days of solar neutrino data accumulated in the upgraded Kamiokande detector (Kamiokande III) are presented. The ^{8}B solar neutrino flux observed in Kamiokande III is $2.82^{+0.25}_{-0.24}\,(\mathrm{stat}) \pm 0.27\,(\mathrm{syst}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$; the combined flux from Kamiokande II and III (2079 days in total) is $2.80 \pm 0.19\,(\mathrm{stat}) \pm 0.33\,(\mathrm{syst}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which is 49% to 64% of the standard solar models. These combined data from January 1987 to February 1995, covering an entire period of solar cycle 22, enabled us to study a correlation between the neutrino flux and the solar activity in detail: no strong correlation of the solar neutrino flux with the sunspot numbers was found within experimental errors. The result on a search for the daytime and nighttime flux difference is also reported. [S0031-9007(96)00925-8]

PACS numbers: 26.65.+t, 95.85.Ry, 96.60.Qc

Solar neutrinos, being observed by the four different experiments [1–4], play crucial roles both in astrophysics and in particle physics. The mechanism of solar energy generation which takes place at the central core of the Sun can be studied directly with solar neutrinos. Evidence of as yet unresolved neutrino properties can be seen by detailed studies of the solar neutrinos. In the previous papers [2] we have demonstrated that the neutrinos are actually coming from the direction of the Sun and that the energy shape of the recoil electron agrees well, within experimental errors, with that predicted from the neutrino spectrum from the beta decay of ^{8}B, the kinematics of $\nu + e \rightarrow \nu + e$ interaction and the detector responses. The absolute flux, however, is about 47% to 61% of those predicted by the standard solar models (SSM) [5,6]. The data obtained from the upgraded phase of the experiment, Kamiokande III (KM-III)—from December 28, 1990 to February 6, 1995—cover the period where the sunspot numbers had been changing from the maximum to the minimum. If one combines the data with those of Kamiokande II (KM-II) (1043 days of data: from January 1987 to April 1990), 2079 days of data in total cover almost the entire period of solar cycle 22 and enable us to study the possible time variations correlated with the solar activity. These high statistics data can also be used to study short-term time variations like the daytime and nighttime flux difference with high sensitivity. Solar neutrinos are supposed to be stable over several million years, and if any time variations were to be found, that would be direct evidence of neutrino magnetic moments [7] or neutrino mass and mixing [8]. A deviation of the recoil electron energy spectrum from prediction is also model independent evidence for finite neutrino mass.

The Kamiokande detector, an imaging water Cherenkov detector placed 1000 m underground in the Kamioka mine, is located about 200 km west of Tokyo. The cylindrical water tank, 15.6 m in diameter and 16.1 m in height, contains 3000 tons of pure water. The inner photosensitive volume, separated by black sheets, contains 2140 tons of water viewed by 948 photomultiplier tubes (PMTs) arranged over the inner surface of the water tank providing the 20% photosensitive area. For the solar neutrino analysis, the most inner part of the detector, consisting of 680 tons of water, was used. The thickness of the water between the cavity wall and the edge of the volume ranges from 10.6 to 11.9 radiation lengths (6.4 to 7.1 nuclear collision lengths) which provides very good shielding for gamma rays and neutrons produced in the rock surrounding the detector.

The detector has been upgraded for the KM-III experiment [9]: More than 100 dead PMTs were replaced, light reflectors which increased the photocoverage from 20% to 25% were newly attached to each inner PMT and new electronics was installed. The number of hit PMTs—PMTs which detected Cherenkov light—has increased by 25% for 10 MeV electrons from 30 hits (KM-II) to 40 hits. The increased number of hit PMT and further efforts to reduce the backgrounds originating from Radon contamination in the water, allowed us to lower the analysis threshold to 7 MeV after December 1991. The trigger threshold—defined at 50% efficiency—has been 5 MeV from the beginning of KM-III. Solar neutrinos are detected through the charged and neutral current interactions off electrons in the water. Although the recoil angles of those electrons keep the neutrino direction within $\sqrt{2m_e/E}$, the angular resolution is mainly determined by multiple Coulomb scattering of the electrons in the water and by the detector response: 26° for 10 MeV electrons for the KM-III detector (28° for KM-II).

The solar neutrino data were not taken about 16.3% of the time due to the calibrations of the detector and other reasons. The selection of good runs was carefully done: The data corresponding to 14.6% of the time were not used for the solar neutrino analysis because of hardware troubles (4.3%), flashing tubes (2.2%), other studies such as cold fusion experiments and tests of the Rn behavior in the water (2.8%), improper water level (1.3%), and others. The present analysis is slightly different from those of KM-II and the ones presented at past conferences. Although the details of the analysis will be described elsewhere [10], the main differences are listed in the following. (1) In the energy calculation, the number of dead tubes must be corrected properly in order to obtain the correct energy. In the previous analyses, the dead PMTs were assumed to be distributed uniformly in the detector and the ratio of the number of dead PMTs to the whole number of PMTs was used for this correction. For the present analysis, however, the actual distribution of the dead PMTs around the Cherenkov pattern was used for the correction. This change minimizes the systematics in the energy calculation, especially in studying the daytime and the nighttime fluxes separately. (2) The dispersion of the index of refraction has been taken into account when the velocity of light in water was calculated, which made the systematic uncertainty in the fiducial volume cut smaller [9]. (3) The cross section of neutrinos on electrons was updated: The radiative correction was included following Bahcall *et al.* [11].

The trigger rate at 5 MeV threshold has been 1 Hz on an average, however, only the data above 7 MeV (7.5 MeV for the first 200 days) were used for the analysis because of the larger backgrounds in the very low energy region. The data were passed through the software filter to remove through-going muons, backgrounds entering from outside of the detector, spallation products, and so on [10]. The final data sample in the fiducial volume of 680 tons with energy above 7 MeV (7.5 MeV) and less than 20 MeV consists of 6368 events.

The angular distribution of the final sample with respect to the Sun is shown in Fig. 1, from which we can extract the solar neutrino signal. The flux, obtained through the maximum likelihood method [2], is $2.82^{+0.25}_{-0.24}\,(\text{stat}) \pm 0.27\,(\text{syst}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$. The systematic error of 9.7% comes mainly from the uncertainty in the angular resolution (7.0%), uncertainties in the energy scale (5.3%), and in the fiducial volume cut (4.0%). All other systematic errors contributed from the uncertainty of the trigger efficiency, the cross section, various cuts, live time calculation, and so on, are less than 1%. The number of solar neutrino events obtained is 390^{+35}_{-33}, whereas expected is 785 for the SSM of Bahcall and Pinsonault (BP) [5]. (We show only the number for the SSM of BP, but the number for the SSM of Turck-Chieze and Lopes (TCL) [6] can be easily obtained.) The ratio to the SSM of BP is $0.496^{+0.044}_{-0.042}\,(\text{stat}) \pm 0.048\,(\text{syst})$.

The KM-II result has been corrected +3.42% before combining with KM-III data, since some of the parameters used in these analyses were different between KM-II and KM-III: i.e., –0.53% for change in $\sin^2\theta_W$ from 0.23 to 0.2317, +3.56% for the radiative correction and +0.39% for the shape of the ^{8}B neutrino spectra—KM-II used the shape of Bahcall and Holstein [12]. The systematic errors are combined by weighting the statistics of each data sample. The resultant combined flux is $2.80 \pm 0.19\,(\text{stat}) \pm 0.33\,(\text{syst}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$.

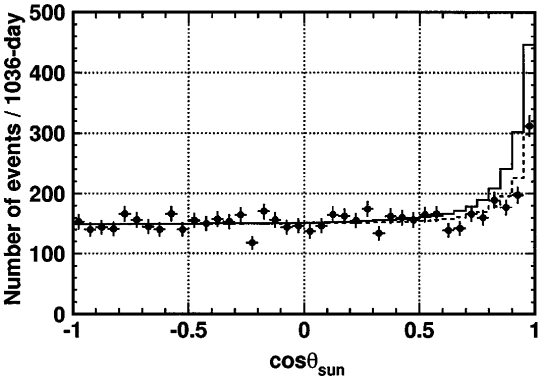

FIG. 1. The $\cos\theta_{\text{Sun}}$ distribution of the final events of the Kamiokande III data (1036 days). The solid line shows the prediction from the standard solar model of Bahcall and Pinsonneault 5 and the dashed line shows the best fit to the data assuming a flat background in the distribution.

The number of the solar neutrino events observed is 597^{+41}_{-40} events for 2079 days of KM-II and KM-III data, whereas the expected number of events is 1213. The flux ratio to the SSM of BP for the combined data is $0.492^{+0.034}_{-0.033}$ (stat) ± 0.058 (syst).

The recoil electron energy distribution relative to the SSM of BP, obtained by using the maximum likelihood method in each energy bin, is shown in Fig. 2. The result is statistically consistent with that of KM-II, and the two results (KM-II and KM-III) were combined. Note that the run time of each energy bin is different since the data were taken with three different thresholds of 9.3 MeV (449 days: KM-II), 7.5 MeV (594 days: KM-II and 200 days: KM-III) and 7.0 MeV (836 days: KM-III). The errors in the lower energy bins are increased not only by the shorter running time but also by the larger backgrounds—this fact basically determined the analysis threshold. The obtained energy shape agrees with the one predicted within the experimental errors. The relative uncertainty of the spectrum was evaluated by Monte Carlo calculation with a shifted energy scale by ±2.2%—the uncertainty of the energy scale [13]. The errors thus evaluated are fully correlated and the resultant range obtained from a smooth fitting is shown in Fig. 2 by the hatched area. It should be noted that an uncertainty in the threshold energy would not cause a serious problem since it affects only the lowest energy bin. We point out that the energy bin near the calibration point (8 MeV) [9] is a guaranteed energy bin. The present result does not reveal any deviations, but the high statistical experiment in the very near future—Superkamiokande—will tell us more about the energy spectrum.

In order to study time variations correlated with the solar activity, the data covering eight years and two months are divided into short-time periods, each consisting of approximately 200 days of data, as shown in Fig. 3. The sunspot numbers have changed from minimum (0 ~ 20) to maximum (~150–200) and back to the minimum again during the experiment. The solar neutrino signal was extracted in each time period. The published results of KM-II [2]—the first five points—have been corrected +3.42% as mentioned before. The statistics of the latter data are larger because of the lower energy thresholds : The energy threshold for each time period is 9.3 MeV for the first two points, 7.5 MeV for the following four points, and 7.0 MeV for the last four points. The relative uncertainty of the flux at each point is 5.3%, which mainly comes from the uncertainty in the energy scale; other systematics are negligible for the relative flux. The correlation of the solar neutrino flux to the sunspot numbers was examined by using the formula data/SSM $= \alpha N_{\rm ss} + \beta$, where $N_{\rm ss}$ is the sunspot numbers averaged over each time period. The result for the ten data points is data/SSM $= (9.4^{+7.2}_{-7.0} \times 10^{-4}) \times N_{\rm ss} + (0.398^{+0.088}_{-0.078})$. This result does not indicate any anticorrelation with the solar activity like the one suggested by the chlorine experiment [1] and rather shows a slight positive correlation which, however, is not significant statistically.

The daytime and nighttime flux difference was also studied [14]. The daytime flux is 2.70 ± 0.27 cm^{-2} s^{-1} and the nighttime flux is $2.87^{+0.27}_{-0.26}$ cm^{-2} s^{-1}: There is no significant difference. If one considers only the ratio,

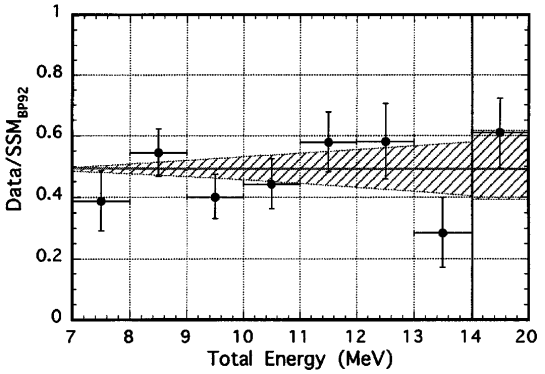

FIG. 2. The recoil electron energy spectrum for the 2079 days of the Kamiokande II and III data. The flux ratio to the standard solar model of Bahcall and Pinsonneault 5 is shown. The hatched area shows the range of systematic uncertainty.

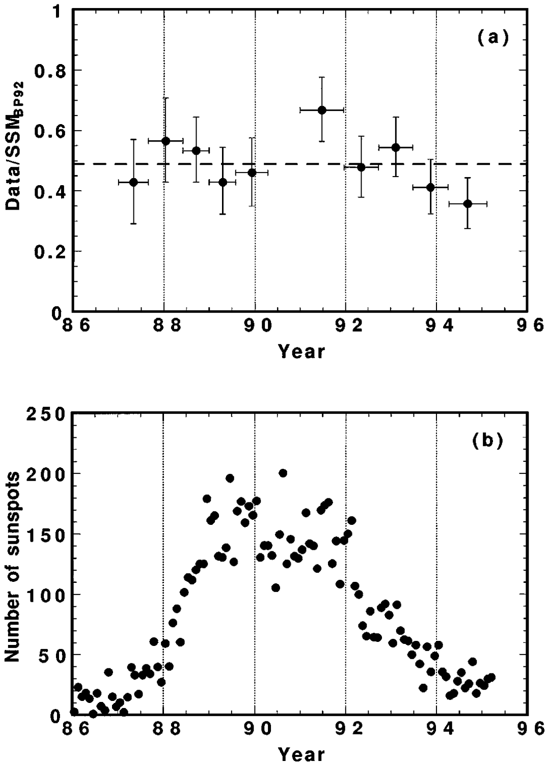

FIG. 3. (a) The flux ratio of the subdivided data to the standard solar model—each consists of approximately 200 days of data. The first five points are the data from KM-II. The dashed straight line is the average flux for the entire time periods. (b) The sunspot numbers. The sunspot numbers reached maximum in 1989 and started to decrease in late 1991.

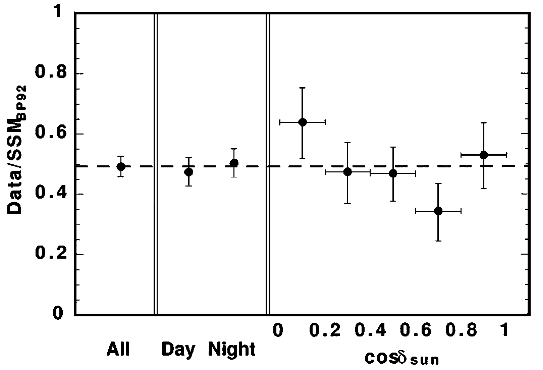

FIG. 4. The solar neutrino flux during the daytime (the Sun is above the horizon) and the nighttime. The nighttime data sample is divided into five subsamples in terms of the direction of the Sun. δ_{Sun} is the relative angle between the direction of the Sun and the z axis of the detector pointing to the center of the Earth.

systematics errors are largely canceled. The systematic error on the relative flux is 2% being estimated by the energy scale for events going upwards and downwards. The nighttime data sample was divided into five subsamples in terms of the cosine of the zenith angle of the Sun relative to the detector z axis as shown in Fig. 4. $\delta_{\mathrm{Sun}} = 0$ corresponds to the direction towards the center of the Earth. No difference is seen among the data points within the statistical errors.

In summary, the solar neutrino results obtained by the KM-III are statistically consistent with the KM-II results although the two experiments have different detector configurations (reflective mirrors) and systematics. The combined data covering the entire period of solar cycle 22 show no anticorrelation with the solar activity and a difference between the daytime and the nighttime fluxes was not observed within the experimental uncertainties.

We gratefully acknowledge the cooperation of the Kamioka Mining and Smelting Company. This work was partly supported by the Japanese Ministry of Education, Science and Culture.

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