THE KAMIOKANDE SOLAR NEUTRINO EXPERIMENT

THE KAMIOKANDE-II COLLABORATION

K. S. HIRATA, T. KAJITA, T. KIFUNE, K. KIHARA, M. NAKAHATA,
K. NAKAMURA, S. OHARA, N. SATO, 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, H.TAKEI[1] AND T.TANIMORI
National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan

M. KOSHIBA
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 M. YAMADA
Niigata University, Niigata, Niigata 950-21, Japan

Y. FUKUDA, K. KANEYUKI, Y.NAGASHIMA AND M.TAKITA
Department of Physics, Osaka University, Toyonaka, Osaka 560, Japan

E. W. BEIER, L. R. FELDSCHER, E. D. FRANK, W. FRATI, S.B.KIM,
A. K. MANN, F.M.NEWCOMER, R VAN BERG AND W.ZHANG
Department of Physics, University of Pennsylvania, Philadelphia PA 19104, U. S. A.

Presented by M. NAKAHATA

ABSTRACT. The observation of ^{8}B solar Neutrinos in the Kamiokande-II detector is presented. Based on 450 days of data in the time period of January 1987 through May 1988, the measured flux obtained with $E_e \geq$ 9.3 MeV was 0.46 ± 0.13 (stat) ± 0.08 (sys) of the value predicted by the standard solar model. The detector and analysis methods were improved since June 1988 and the background level has been decreased by a factor of about three since then.

1. Introduction

The discrepancy in the solar neutrino flux between the ^{37}Cl experiment [1] (2.1 ± 0.3 SNU; 1 σ error) and the prediction by the standard solar model(SSM)[2] (7.9 ± 2.6 SNU;

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[1] On leave from Niigata University

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3 σ error) is known as the missing solar neutrino problem. There have been many possible explanations to this discrepancy.[3, 4, 5] In order to solve this problem we need more observational data on solar neutrinos. Moreover, the recent result from the ^{37}Cl experiment gives a high neutrino flux[6] (4.2 ± 0.7 SNU) and an anti-correlation of the solar neutrino flux with solar activity is suggested.[6] In order to check these results several independent experiments should be performed.

The Kamiokande-II is an imaging water Cherenkov detector, which detects ^{8}B solar neutrinos by neutrino-electron scattering, $\nu_e e^- \rightarrow \nu_e e^-$, and yields information on the neutrino arrival time, the direction, and the energy spectrum.

2. Detector

The schematic view of the Kamiokande-II detector is shown in Fig.1. It is described in detail in ref.[7]. The detector volume contains 2140 tons of water, which is viewed by an array of 20-in.-diameter photomultipliers tubes (PMT) on a 1×1-m^2 lattice on the surface. The photocathode coverage amounts to 20 % of the total inner surface. The attenuation length of Cherenkov light in the water is usually in excess of 45 m. The inner detector is completely surrounded by a water layer (anti-counter) of thickness ≥ 1.4 m. The anti-counter is an absorber of γ-rays from surrounding rocks and a monitor of cosmic ray muons. The fiducial volume of the detector is 680 tons, which is 2 ~ 3 m inside from the wall of the detector.

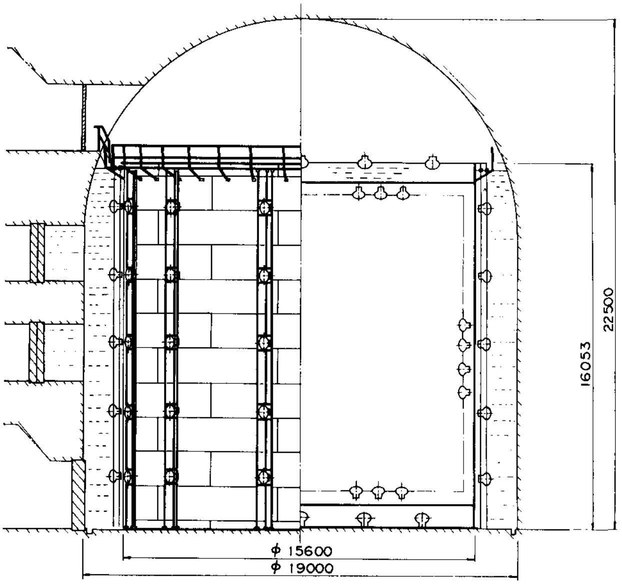

Figure 1. Schematic view of the Kamiokande-II detector. The inner detector is viewed by 948 20-in.-diameter PMTs. The anti-counter surrounds the inner detector and is viewed by 123 PMTs. Dimensions in the figure are in millimeters.

The detector was triggered by at least 20 hit PMT's within 100 nsec. Charge and time information for each PMT above threshold was recorded for each trigger. The trigger accepted 7.6 (6.7) MeV electrons with 50 % efficiency and 10 (8.8) MeV electrons with 90 % efficiency over the fiducial volume of the detector. These numbers were the values before October 1987 (October 1987 - May 1988).[1] The raw trigger rate was about 0.6 (1.2) Hz of which 0.37 Hz was cosmic-ray muons. The remaining rate was due to radioactive contamination in the detector and external γ-rays. The Cherenkov light of an electron of 10 MeV total energy fired ~ 26 PMTs. The energy calibration was performed with γ-rays of energy up to 9 MeV from the reaction Ni(n, γ)Ni, with electrons from μ decays, and with spallation products by cosmic ray muons. From these calibrations, the absolute energy normalization was known to be better than 3 %. The energy resolution was expressed by 22 % $/(E_e/10\ \mathrm{MeV})^{0.5}$ and angular resolution for an electron of 10 MeV was 28°, respectively.

3. Data Selection

The first search for ^{8}B solar neutrinos was carried out on the 450 days of data taken from January 1987 through May 1988.

First of all, events that satisfy following three criteria were selected:

(1) The total number of photoelectrons (p.e.) per event in the inner detector should be less than 100, corresponding to a 30 MeV electron.
(2) The total number of photoelectrons in the outer detector is less than 30 for ensuring containment of an event.
(3) The time interval from the preceding event should be longer than 100 μsec to exclude electrons from μ decays.

The event rate after the selection is shown in (a) in Fig.2.

The vertex positions and the directions of the selected events were reconstructed with an algorithm based on the time and position of hit PMTs. The rms vertex position resolution is 1.7 m for 10 MeV electrons. By limiting the events in the fiducial volume of 680 tons, the backgrounds of external γ-rays are reduced. As shown in (b) in Fig. 2, the fiducial volume cut reduces the event rate by an order of magnitude.

Most of the remaining events were found to be due to unstable spallation products of through-going muons in the detector. These beta-decay events have time and spatial correlation with the preceding cosmic ray muons. Furthermore, these preceding muons often accompany energetic cascade showers. These spallation events were reduced by criteria which take into account these features. The details of the criteria was described elsewhere.[8] They reduced the event rate with $E_e \geq 10$ MeV by 70 % (Fig.2 (c)) whereas the introduced dead time of 10.4 %.

One of the remaining background after the reduction of spallation backgrounds was external γ-rays which are not completely eliminated by the fiducial volume cuts. To reduce them, events were rejected which had vertex positions near the edge of the fiducial volume (outer 1 m layer) and directions inward (cosine of the angle relative to the normal to the nearest wall > 0.67). This cut further reduced the event rate ~ 40 %, and introduced an additional dead-time of 13 %.

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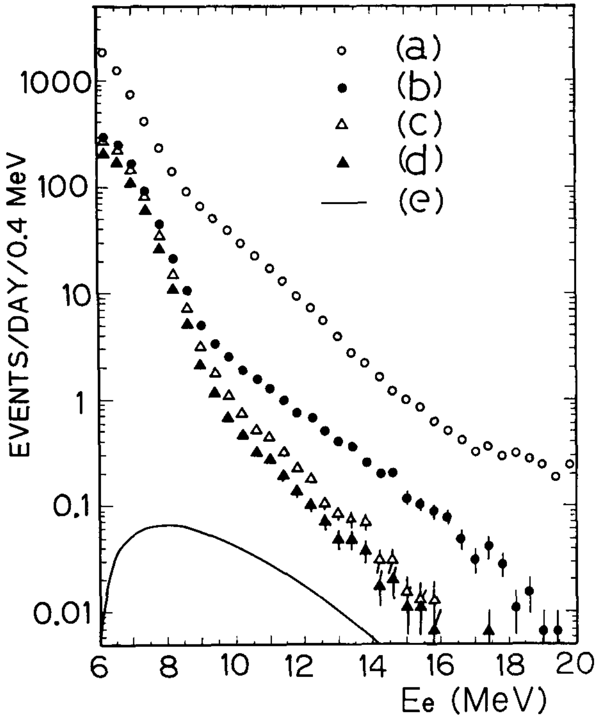
[1] The trigger thresholds are 6.1(5.2) MeV with 50 % efficiency from June 1988 through April 1989 (since May 1989), respectively.

The whole processes of the data analysis were performed also to solar neutrino signals generated by a Monte Carlo simulation and an expected spectrum from SSM was calculated, which is shown in Fig.2 (e).

Figure 2. Differential energy distribution of low energy events (a) in the total mass of 2140 tons; (b) in fiducial mass of 680 tons; (c) after the spallation cut; (d) after remaining γ-ray cut; (e) Monte Carlo prediction of SSM after all cuts.



4. Intensity of ^{8}B Solar Neutrino Signal

The selected event sample was then tested for a directional correlation with the sun. Figure 3 shows the $\cos\theta_{sun}$ distribution of the events with $E_e \geq 9.3$ MeV and $E_e \geq 10.1$ MeV, in which $\cos\theta_{sun} = 1$ corresponds to the expected direction to the earth from the sun. One sees a clear enhancement near $\cos\theta_{sun} = 1$. The solid histograms in the figure gives the signal expected from a Monte Carlo simulation based on the SSM. The figure indicates that the observed signal is less than the expectation from SSM. The energy spectrum of the ^{8}B solar neutrino signal is obtained by fitting the $\cos\theta_{sun}$ distribution with a flat background plus an expected angular distribution of the signal for the data in each energy bin. The obtained energy spectrum is shown in Fig.4 with the expectation from the SSM

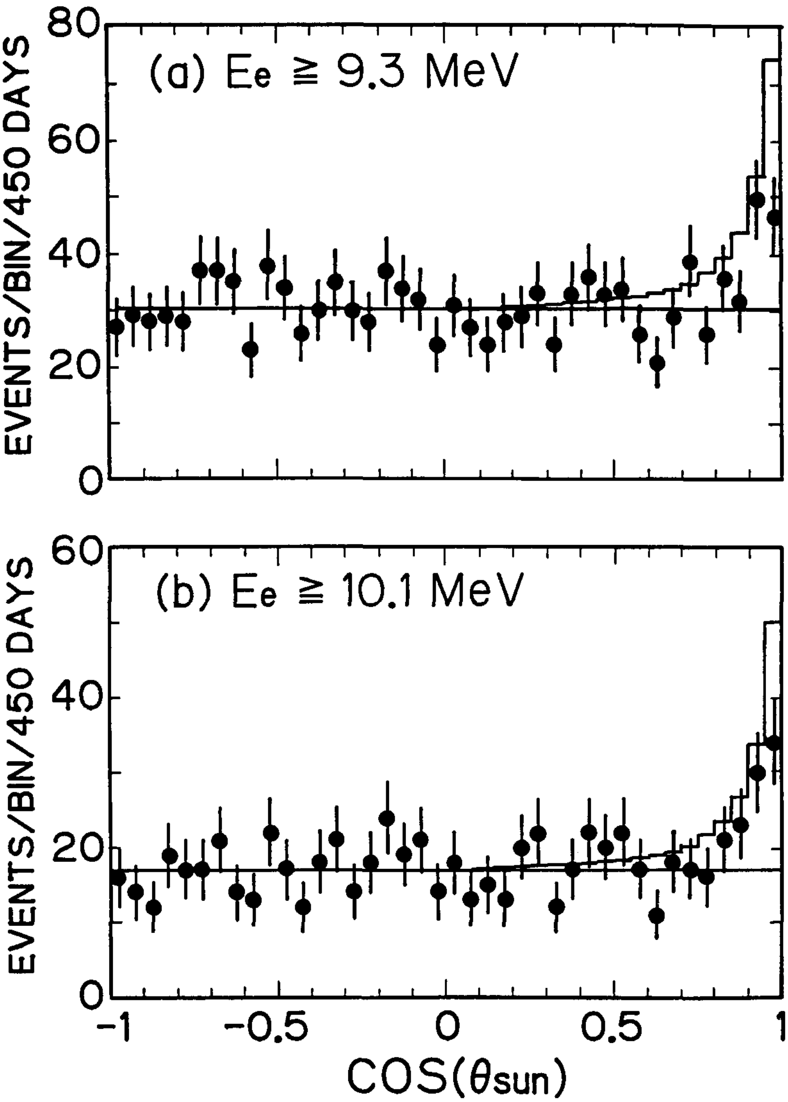


Figure 3. Distributions in $\cos\theta_{sun}$, cosine of the angle between the reconstructed direction of an electron and the direction from the sun to the earth, for the events with (a) $E_e \geq$ 9.3 MeV and (b) $E_e \geq$ 10.1 MeV.

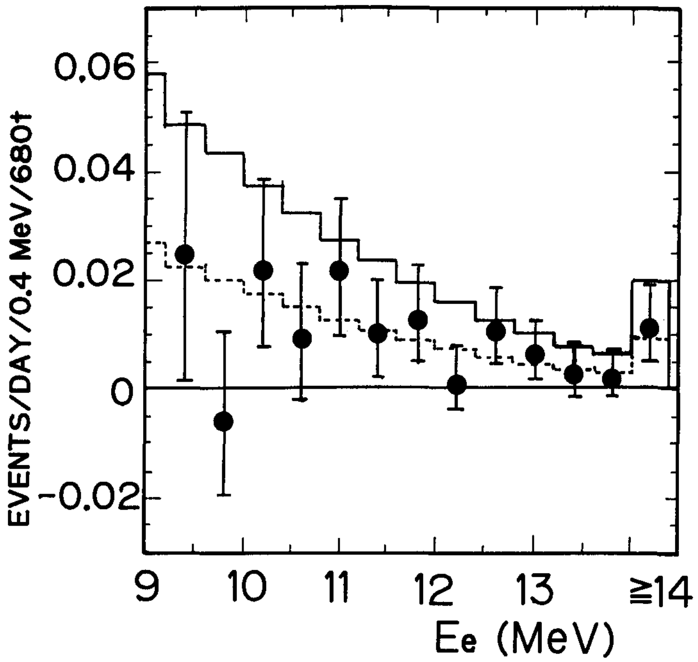


Figure 4. Energy distribution of the solar neutrino signal. The solid histogram shows the prediction from SSM. The dotted histogram shows the best fit to the data.

by a solid histogram. The flux of the ^{8}B solar neutrinos is obtained by fitting the electron energy spectrum by scaling the expected spectrum. The obtained flux was :

$$\frac{\text{Kam-II data}}{\text{SSM}} = 0.46 \pm 0.13(\text{stat}) \pm 0.08(\text{sys}) .$$

The best fit of the spectrum is shown by the dotted histogram in Fig. 4. The systematic error was determined mainly by the uncertainties in energy calibration and angular resolution.

This result is statistically consistent with the value obtained by the ^{37}Cl experiment in essentially the same time period.[6] The result of the Kamiokande-II confirmed the missing solar neutrino problem.

5. Present Status

The sources of the remaining backgrounds after all cuts were : (a) radioactivities in the detector materials; (b) spallation products and external γ-rays which were not completely eliminated by the above cuts, where backgrounds of (a) and (b) dominated at relatively lower energy ($E_e \leq 9$ MeV) and at higher energy ($E_e \geq 9$ MeV), respectively. These backgrounds can be reduced by improving the energy resolution, vertex position resolutions and methods of cuts. Therefore, we have performed following improvements since June 1988.

(1) Gain of the PMTs were increased by a factor of two.

The effects of the PMT gain increase were : (i) ~ 20 % increase of hit PMTs corresponding to unit deposited energy by electrons[1]; and (ii) ~ 10 % improvement of the energy resolution (now 19.5 % $/(E_e/10\ \mathrm{MeV})^{0.5}$) for low energy electrons. The increase of the number of hit PMTs in an event improved event vertex resolution, and this led to reduction of poorly reconstructed events in the fiducial volume.

(2) The method of the spallation cuts was improved.

The criteria for spallation products of longer life time were improved. The improved criteria reduced the remaining background due to spallation products by a factor of about two.

Figure 5 compares the present final event rate with that before the improvements. The background rate was reduced by a factor of about three. Furthermore, this improvement enabled us to lower the energy threshold of the data analysis to ~ 7.5 MeV. The result of the recent data will be presented in near future.[9]

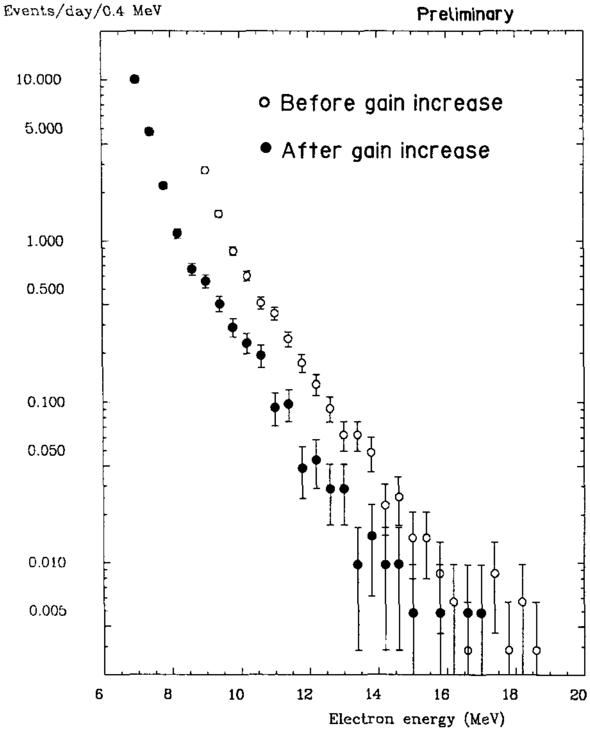


Figure 5. Differential energy distribution of low energy events after applying all cuts for the data before and after the improvements. The dead time due to the cuts is corrected.

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[1] The PMT gain was increased without changing the discriminator threshold for each PMT. Thus, the collection efficiency of a single photoelectron level was increased and, consequently, the number of hit PMTs in an event was increased.

6. Conclusion

The observation of ^8B solar neutrinos in the Kamiokande-II detector was presented. The measured flux was 0.46 ± 0.13 (stat) ± 0.08 (sys) of the value predicted by the standard solar model, which was obtained based on 450 days of data in the time period of January 1987 through May 1988 with $E_e \geq$ 9.3 MeV. The backgrounds to the solar neutrinos were reduced by a factor of about three after June 1988 by increasing the gain of PMTs and by improvements of cuts. This enabled us to lower the energy threshold of the data analysis to ~ 7.5 MeV. The statistical error of the recent data should be much smaller than before.

7. Note Added

After the conference, the recent solar neutrino data was analyzed. Based on 288 days of improved data taken in the time period of June 1988 through April 1989, the measured flux obtained from the data with $E_e \geq$ 7.5 MeV was 0.39 ± 0.09 (stat) ± ~0.06 (sys) (preliminary) of the value predicted by the standard solar model.[9]

8. Acknowledgements

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