REAL TIME, DIRECTIONAL MEASUREMENT OF ^{8}B SOLAR NEUTRINOS IN THE KAMIOKANDE-II DETECTOR

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ABSTRACT:

Neutrinos from the decay of ^{8}B in the Sun have been observed in the Kamiokande-II detector. Based on 740 live detector days in the time period January 1987 through April 1989, the measured flux for $E_e \geq 9.5$ MeV is 0.39 ± 0.09 (stat.) $\pm$ 0.07 (syst.) of the value predicted by the standard solar model. Within statistical errors, no evidence for either a day-night or seasonal difference is found in the present data.

According to the standard solar model (SSM)[1], the Sun is an intense source of low energy electron type neutrinos (ν_e)[2] that are products of the nuclear processes at high temperature near its center. The motivation of solar neutrino observation lies in solar physics and elementary particle physics: (1) it will be a sensitive test of the SSM by probing the interior of the Sun unlike the photons emitted from the surface layer; (2) it will provide a means of studying the intrinsic neutrino properties that may be revealed by the great distances that neutrinos travel in passing from the core of the Sun to a detector at Earth.

In addition to these fundamental motivations, there exists an unsolved discrepancy in the solar neutrino flux between the result of ^{37}Cl experiment and the prediction of the SSM. The average total rate of ν_e interactions in the ^{37}Cl detector from 1970 to the end of 1985 was $2.1 \pm 0.3(1\sigma)$ SNU[3] compared to the value of $7.9 \pm 2.6(3\sigma)$ SNU predicted by the SSM[2], where a solar neutrino unit (SNU) is 10^{-36} interactions per target atom per second. This discrepancy has stimulated speculations relating to reconsideration of the SSM, as well as speculations involving as yet unobserved intrinsic properties of neutrinos. Furthermore, an anticorrelation of the solar neutrino flux with the number of sunspots, i.e., with solar magnetic cycle ($\sim$ 11 years) was inconclusively observed in the ^{37}Cl experimental data for the last two decades. This will be further tested and continue to be monitored by all existing and coming solar neutrino detectors.

In a previous paper[4], we described the observation of ^{8}B solar neutrinos in the Kamiokande-II detector based on 450 days of data in the time period of 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 SSM, to wit, 0.46 ± 0.13 (stat.) $\pm$ 0.08 (syst.), for observed recoil electron total energies of $E_e \geq 9.3$ MeV. The neutrino signal was clearly emanating from the Sun, and the observed shape of the differential energy spectrum was consistent with that predicted from the product of the ^{8}B decay spectrum[5] and the cross section for $\nu_e e^- \rightarrow \nu_e e^-$, which is the reaction for detecting low energy ν_e in Kamiokande-II.

The Kamiokande-II detector has continued to measure the solar neutrino signal with an improvement of the detector in June 1988 by operating the photomultiplier tubes

(PMT) at higher voltage (PMT gain increased by a factor of two)[6]. In this report, we describe a real time, directional measurement of ^{8}B solar neutrinos based on the combined 740 days of data taken in the period of January 1987 through April 1989, and discuss the searches for day-night and seasonal differences of the measured solar neutrino flux in that data.

The Kamiokande-II is an imaging water Čerenkov detector (total useful mass 2140 metric tons) located 1000 m underground in the Kamioka mine in Japan[7]. The detector was initially designed to search for nucleon decays. The upgraded version, Kamiokande-II, incorporates all the features of the earlier version, and includes some modifications, additions and improvements crucial for detecting low energy neutrinos: (1) a 4π solid angle anticounter is important as shielding against gamma-rays and neutrons entering the detector as well as for vetoing events coming from the outside such as cosmic ray muons; (2) a new electronics system provides multihit time and charge measurement capacity for each PMT, and therefore achieves better event reconstruction especially for low energy events; (3) a more elaborate water purification system reduced the radioactivity in the water, as a result of which the trigger threshold can be set at 7.5 MeV.

The main backgrounds in the solar neutrino measurement in Kamiokande-II are natural radioactivity (beta-decay of ^{214}Bi; a daughter of ^{222}Rn) in the detector water at relatively low energies ($E_e \leq 9$ MeV), and and gamma-rays emanating from the rock surrounding the detector and beta-decays of cosmic ray muon-induced spallation nuclei at relatively high energies ($E_e \geq 9$ MeV).

The data analysis consists of: (1) data reduction to select low energy contained events and reject noise events; (2) fiducial volume (680 tons; 2 m inside the barrel and bottom PMT layers and 3.14 m inside the top PMT layer) cut to reject most external gamma-rays; (3) spallation cut to reject background events due to cosmic ray muon-induced spallation products. A detailed description of the analysis is given in Refs. (4) and (8).

The total observed event rate after the spallation cut is 4 events/day with $E_e \geq 9$ MeV, which is an order magnitude larger than the expected solar neutrino signal by the SSM. Since background events do not have a directional correlation with the Sun at a given time,

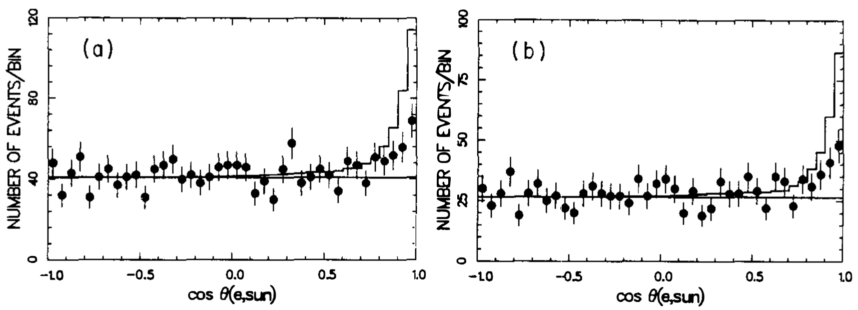

Figure 1: Distributions in $\cos\theta_{(e,Sun)}$ of 740 live days of data for (a) $E_e \geq 9.5$ MeV, and (b) $E_e \geq 10.0$ MeV. $\theta_{(e,Sun)}$ is the measured angle between the trajectory of each observed electron at a given time and the direction from the Sun at that time.

the directional test with respect to the Sun of each event will provide an additional order of magnitude discrimination against background. Fig. 1 shows the $\cos\theta_{sun}$ distributions for E_e threshold values of 9.5 MeV and 10.0 MeV from the entire 740 live days of observation during the period January 1987 through April 1989. The distributions exhibit a clear solar neutrino signal emanating from the Sun ($\cos\theta_{sun} = 1$). The analysis was repeated with incorrectly assigned latitudes and longitudes of the detector to the sample. The statistically significant signal peaks only at Kamioka as shown in Fig. 2. The differential recoil electron energy distribution from the 740 day sample is shown in Fig. 3, where it is compared with the expected spectral shape.

In Fig. 4 is plotted Data/SSM for the day (Sun above the horizon) data and the night (Sun below the horizon) data from the 740 day sample, where SSM in the denominator is the Monte Carlo calculated simulation of an observation based on an arbitrary chosen SSM (here, we took the incident ^{8}B solar neutrino flux based on the SSM given in the Ref. (5)). Accordingly, the relative positions of the points in this plot are independent of predicted absolute values. It was suggested that a fraction of ν_e converted by the MSW effect in the Sun[9] could be regenerated in the Earth. Thus, the solar ν_e flux observed at night in the Kamiokande-II detector might be expected to be higher than that observed

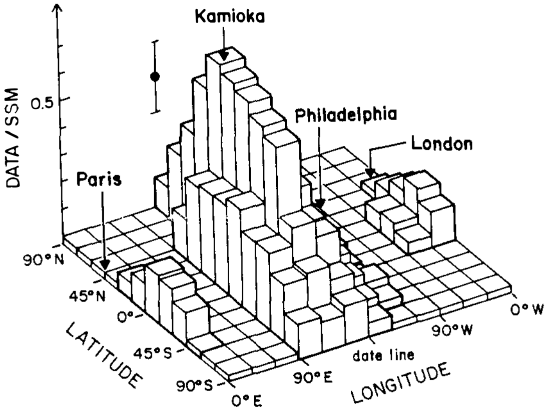

Figure 2: Lego plot of the measured ^{8}B solar neutrino yields with incorrectly assigned latitudes and longitudes of the Kamiokande-II detector to the data sample.

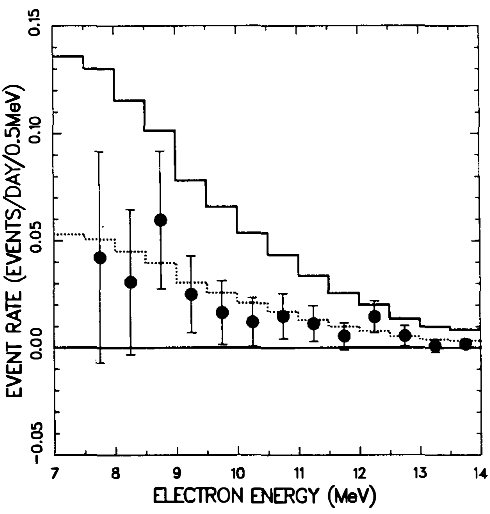

Figure 3: Differential total energy distribution of the recoil electrons from $\nu_e e^- \rightarrow \nu_e e^-$ from 740 day data. The solid line corresponds to the value expected from the SSM; the dotted line corresponds to the value 0.39 times the value expected from the SSM.

in the day if matter oscillations were taking place. Within the statistical errors, the data in Fig. 4 show no day-night difference. The ratio Night/Day in Fig. 4 is 1.15 ± 0.5 for $E_e \geq 9.5$ MeV.

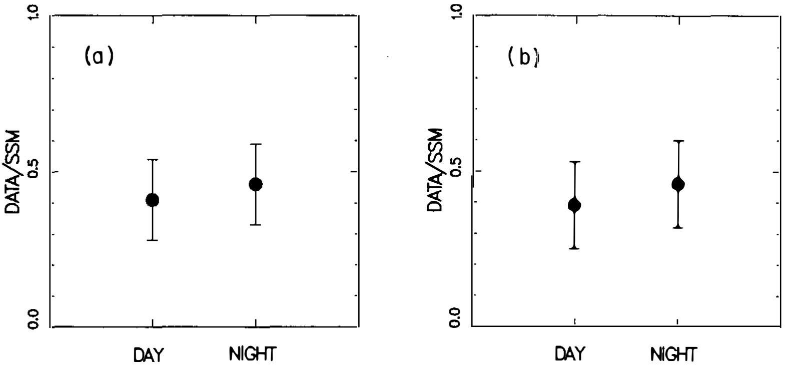

Figure 4: Plots of the day and night ^{8}B solar neutrino yields from the 740 day data sample for two threshold energies, (a) $E_e \geq 9.5$ MeV, and (b) $E_e \geq 10.0$ MeV.

In Fig. 5 is plotted the ratio Data/SSM for different Earth seasons. A small (probably less than a 10 %) difference in the ^{8}B solar neutrino flux might be expected due to different inclination of the axis of the solar magnetic field relative to Earth at the different seasons[10]. Within statistical errors, there is no seasonal difference exhibited by the data. The ratio I/II in Fig. 5 is 0.95 ± 0.4 for $E_e \geq 9.5$ MeV.

The total sample of the 740 day live detector exposure in the interval January 1987 through April 1989, yields the ^{8}B solar neutrino flux for $E_e \geq 9.5$ MeV

$$\frac{\text{Data}}{\text{SSM}} = 0.39 \pm 0.09\,(\text{stat.}) \pm 0.07\,(\text{syst.})$$

relative to the value predicted by the SSM[5].

Despite the limited statistics and the relatively high energy threshold in Fig. 3, the Kamiokande-II results taken in conjunction with the ^{37}Cl result (2.1 ± 0.3 SNU averaged over the period 1970-1985)[3] suggest that the so-called adiabatic solution in the MSW

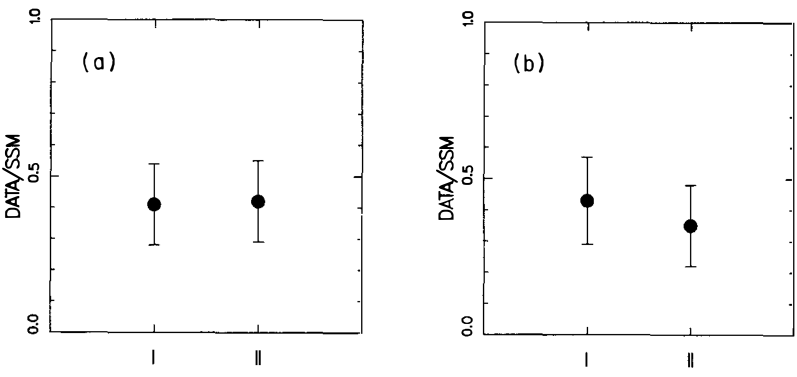

Figure 5: Plots of two different Earth season ^{8}B solar neutrino yields from the 740 day data sample for (a) $E_e \geq 9.5$ MeV, and (b) $E_e \geq 10.0$ MeV. The point at I is for data taken at the beginning of June and beginning of December, when the Earth's orbit intersects with the equatorial plane of the Sun. The point at II is for data taken at the beginning of September and beginning of March, when the Earth is maximally distant from the the equatorial plane of the Sun, and therefore the neutrinos arriving at Earth pass across a strong toroidal solar magnetic field.

effect is disfavored. Continued data-taking for monitoring of the time dependence of the ^{8}B solar neutrino signal for at least another year would provide an important test of a possible anticorrelation of the measured solar neutrino flux with solar activity, since the number of sunspots increases rapidly from the beginning of 1989 and reaches its maximum during 1990.

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