RECENT RESULTS ON SOLAR NEUTRINOS FROM KAMIOKANDE-II

The Kamiokande-II Collaboration

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ABSTRACT

Results on solar neutrinos from Kamiokande-II, based on 1040 days data sample from January 1987 to April 1990, was presented. The measured flux of ^{8}B solar neutrino is 0.46$\pm$ 0.05 (stat.)$\pm$ 0.06(syst.), which is normalized to the predicted flux of the Standard Solar Model. Differential Energy spectrum of recoil electron also provides unequivocal evidence for the production of ^{8}B neutrino by fusion in the Sun. Analysis of the MSW effect was carried out,and the adiabatic region, $7.2\times10^{-4} \leq \sin^2 2\theta \leq 6.3\times10^{-2}$, $\Delta m^2 \sim 1.3\times10^{-4}$ (eV)^2 is excluded with 90% C.L. from the energy spectrum constraint.

Time variation of the solar neutrino flux in this period was not observed within the statisitcal errors. In addition, short-time varitaions were examined; within the statitical error, no significant variation was observed.

The solar neutrino problem has been one of most interesting and challenging issues in both astrophysics and particle physics for this two decades. Since the ^{37}Cl experimnent by Davis et al.[1] reported the considerably large deficit of the solar neutrio flux from the predicted values of the Standard Solar Model (SSM)[2], a lot of ideas to explain this discrepancy have been proposed, for example, the modification of the SSM or other types of the solar model(non standard solar model) from astrophysics, and neutrino oscillations into other flavor types, neutrino magnetic moment and neutrino decay from particle physiscs[3]. It seems to be difficult to find a solution only in the astrophyiscal mechanism inside the Sun, beacuse the SSM is the most established and well-known theory in astrophysics and can predict the features of not only the Sun but also other stars in the Universe except the solar neutrino problem. Therefore, the solar neutrino problem could be a clue of unknown new physics. Anyway, the existence of the deficit of the solar neutrino flux should has been reconfirmed by other independent excperiments. In 1988, the Kamiokande-II collaboration observed the same level deficit of the solar neutrino flux based on 450 days data sample by a totally different method using a water Cherenkov detector[4]. Solar neutrino observation in Kamiokande-II has been continued until April 1990, and new results have been published recently[5,6,7]. Followings are the summary of the new results concerned with the solar neutrino problem based on 1040 days data sample from January 1987 to April 1990.

In Kamiokande detector, the elastic neutrino-electron reaction ($\nu_e e \rightarrow \nu_e e$) is mainly observed by detecting Chrenkov light emitted from a scattered electron in water. Almost all of the momentum and energy of the incoming neutrino change into the forward outgoing electron in this reaction, which is a significantly different feature from the experiments using the inverse β reaction like the ^{37}Cl experiment. Kamiokande-II therefore provides two independent informations, the direction and energy spectrum, to detect solar neutrino. Especially the directionality allows us to separate clearly the solar neutrino signals from the huge background events which have no correlation with the direction of the Sun. In addition, Kamiokande-II has a good ability of the real time measurement which enables to search for the short time variations of the flux, like a day-night effect.

Kamiokande is located underground in 1000m depth in Kamioka Mine. Kamiokande detector is a water-Cherenkov type, and contains 3000 tons of very pure water, where the central region of 680 tons is used as a fiducial volume for solar neutrino observation. 948 photomultipliers(PMTs) of 20 inch diameter are placed on the cylindrical wall of the inner tank with 14.4mϕ x 13.1 m height to measure the timing and amount of Chrenkov light. Outside of the inner tank, the anti counters with 123 PMTs of 20 inch diameter are placed in order to veto both cosmic rays and gamma rays emitted from surrounding rocks.

The charge and timing of hit PMTs are measured, and this information is used to reconstruct the vertex position, direction and energy of events. For low energy events like solar neutrino events($E_e \leq$50MeV), we can estimate their energy by counting the number of hit PMTs, where the attenuation of light in water and the effective photosensitive area of the PMTs are corrected. The energy resolution is estimated to be 20% for a 10 MeV electron.

In order to obtain the the absolute solar neutrino flux, it is essential to estimate the absolute energy normalization with the accuracy of less than a few %. The energy caliblation is carried out by using the discrete gamma ray of about 9 MeV emitted from the neutron absorption reaction of Ni(n,γ)Ni, and the absolute value of energy is determined within 3% accuracy. The vertex position and angular resolution are estimated as 1.0m and 28^o respectively for a 10 MeV electron; here the angular resolution includs the large effect of multipule scattering of electrons in water. The trigger efficiency for electrons traversed in the fiducial volume is 50% for 6.1 MeV and 90% for 9.2 MeV. From June 1988, the gain of PMTs was increased by a factor 2 to improve the response of the detector for a low energy event. The parameters of Kamiokande-II mentioned here are those obtained after gain doubling. The parameters before gain doubling are described in Refs.4 and 8. Due to the improvement of the detector and the reduction of the isotopes in water (mainly ^{214}Bi), the energy threshold for the final data sample was achieved to be 7.5 MeV after gain doubling (9.3 MeV before gain doubling).

The data from Kamiokande-II contain huge background events, although the event rate of solar neutrinos expected from the SSM is only about 0.8 events/day for $E_e \geq$7.5 MeV. There are several background sources in the Kamiokande detector. Main sources are gamma ray from surrounding rocks and materials, and β decay of ^{214}Bi which is a daugther element of ^{222}Rn. Spallation events which are induced by unstable nuclei produced by cosmic-ray muons are another main background events for solar neutrino signals. In order to search for solar neutrino events in the huge background events, we applied some sophisticated cuts in the off-line analysis to reduce background events. At the first stage of the data reduction, events occurred in the fiducial volume of 680 tons were selected, where most of gamma rays from rocks of which vertex positions were near the wall of the detector were excluded. Next, spallation events were rejected by sophistcated cuts in which proximity in space and time between preceding cosmic-ray muons and the following low energy events were taken into account. At last, part of gamma rays from rocks was excluded by examining the direction of events which were produced in the 1m thick layer near the edge of the fiducial volume; if the direction of such an event points inward and vertical to the wall, it was rejected. The data reduction is described in detail in Ref.8.

For the final data sample, the correlation between the solar direction and the event direction are examined. Figs.1(a) and (b) show the cos θ_{sun} distributions of the final data sample for 7.5 MeV and 9.3 MeV energy threshold respectively, where θ_{sun} is defined as a angle between the direction of the Sun and the direction of the scattered electron. The solid line in this figure represents the expected solar neutrino flux from the SSM including the detecor response. A clear forward peak is apparent, which is the evidence that neutrinos really come from the Sun. The number of events in the peak is however significantlly fewer than the prediction of the SSM. The resultant flux values of ^{8}B solar neutrino for total 1040 days data sample and later 590 days data sample are given by

Data/SSM=0.46± 0.05(stat.)±0.06(syst.), and

Data/SSM=0.45±0.06(stat.)±0.06(syst.)($E_e \geq$ 7.5 MeV)[5].

There is no siginificant difference between the relative flux of the 450 days sample [0.48± 0.09(stat.)±0.08(syst.)($E_e \geq$ 9.3 MeV)] and 590 days sample. From this result, the deficit of the solar neutrino observed by Davis et al. has been reconfirmed by the independent experiment of Kamiokande-II. Differential energy spectrum of recoil electrons is also obtained as shown in Fig.2. The shape of the spectrum indicates the consistency with that of expected from the β decay of ^{8}B in the Sun.

For the new results on solar neutrino, the study of the MSW effect[9] was carried out. First, some characteristics of the MSW effect for solar neutrinos observed on the earth are breifly summarized. The MSW effect is now considered to be the best candidate for explainig the defifict of solar neutrino without any sophisticated tricks, although it cannot provide a unique solution for the oscillation parameters of Δ m^2 and sin^2 2θ[10]. There exists three typical solutions in oscillation parameter space corresponding to the adiabatic, non-adiabatic, and large mixing angle solution. These solutions of the MSW effect show characteristic features in the energy spectra respectively. The adiabatic and non-adiabatic solutions predict the suppression of higer energy neutrinos and the suppression of lower energy neutrinos. The large mixing angle solution predicts that the day-night and seasonal time variations would be appeared by the regeneration of ν_μ, which is produced in the Sun by the MSW effect, to ν_e again in the earth. Fig.3 shows the comparison of observed differential energy spectrum of recoil electrons with those predicted from three solutions, where all energy spectra are normalized to the spectrum expected from the SSM. In this comparison, the adiabatic solution is clearly less favored than other two solutions. The confidence contour at the 90%C.L. for the allowed region in the oscillation parameter space is shown in Fig.4, where both the total flux and the energy spectrum are taken into account. Clearly the adiabatic solution with Δm^2 $\sim$ 1.3$\times$10^{-4} (eV)^2, 7.2$\times$10^{-4} $\leq$sin^{2}2$\theta$$\leq$6.3$\times$10^{-2} is excluded by the constraint from the differential energy spectrum[6]. The same contour of the ^{37}Cl experiment is also drawn in this figure. Note that there are two good overlap regions, "so-called" non adiabatic region and the region corresponding to the adiabaic region with large mixing angle. These overlap regions suggest that the results of ^{71}Ga experiment should be less than 100 SNU, which is consistent with the preriminary result from SAGE[11].

In Fig.5, the summary of the short time variations such day-night, seasonal and semiannual is presented, where all data were corrected for less than 6% due to the eccentricity of the earth orbit. As shown in this figure, no significant time variations are observed within statistical errors. In order to study the regeneration in the earth more precisely, the data sample is divided according to the path length of neutrino coming through the earth, and the distribution of solar neutrino for the this path length is examined with the predictions. Consequently, the parameter region, sin^{2}2θ $\geq$ 0.02 and Δm^2=2$\times$10^{-6} $\sim$ 10^{-5}(eV)^2, is excluded at 90% C.L. without any assumption on the absolute value of the expected solar neutrino flux. Detail of short time variations is described in Ref.7.

The ^{37}Cl experiment presented the other interesting result of the anti-correlation of the solar neutrino flux with the sunspot activity[12]. Voloshin, Vysotsky and Okun proposed that it indicated the possible existence of an unconsiderably large neutrino magnetic moment[13]. If the magentic field in the convective zone of the Sun is large enough to be a few kG and the neutrino magnetic moment is as large as $\sim 1\times10^{-10}\mu_B$, the spin of solar neutrino would flip, and its helicity changes from left-handed to right handed; right-handed neutrino does not interact via weak interaction. If neutrinos has such a large magnetic moment, two characteristic time variations are expected to be observed. One is the anti-correation with the sunspot number. During the solar acivity minimum, the strength of the solar magnetic field decreases into one of tenth of the solar magnetic fields at the solar acivity maximum. The other is a semiannual time variation which we mention later in detail. The 1040 days data sample is divided to five time intervals of 200 live days, and the Data/SSM ratios are plotted in Fig.6(a). Also, the time variation of the sunspot number during the same period is drawn in Fig.6(b)[14]. There observed no anti-correlation between the sunspot number and the solar neutrino flux larger than statistical errors.

Furthermore, the possible existence of the neutrino spin precession in the solar magnetic field predicts a seasonal variation of the solar neutrino flux. Since the solar magnetic axis is tilted to the ecliptic plane by 7 degree, neutrinos emitted from the core of the Sun come out through the equatorial region in June and December, where the magnetic field is changing its sign and the strength of magnetic field is relatively small. While in March and September neutrinos pass through the relatively stronger magnetic field region outer of the equatorial region. In order to search for this oscillational effect, a year was divided into two periods as follows, Period I :(April 22 - July 21)&(Octber 21 - January 20) and Period II :(January 21 - April 21)&(July 22 - October 20). The relative fluxes to the averged value for period I and II are 0.94 ± 0.16(stat.) and 1.06 ± 0.15(stat.) respectively, and plotted in Fig.5. To study this effect further, more restricted time intervals were selected. The relative fluxes from one-month time periods corresonding to the time that the solar neutrinos just pass through the weakest magnetic field region or the strongest region are 0.71 ± 0.27(stat.) and 1.12 ± 0.26(stat.) respectively.

All results from Kamiokand-II do not show any siginificant time variations indicating the anti-correlation with the strength of the magnetic field in the Sun. Consequently, any possible evidence for a magnetic interaction of solar neutrino in the Sun was observed within the experimental sensitivity of Kamiokande-II.

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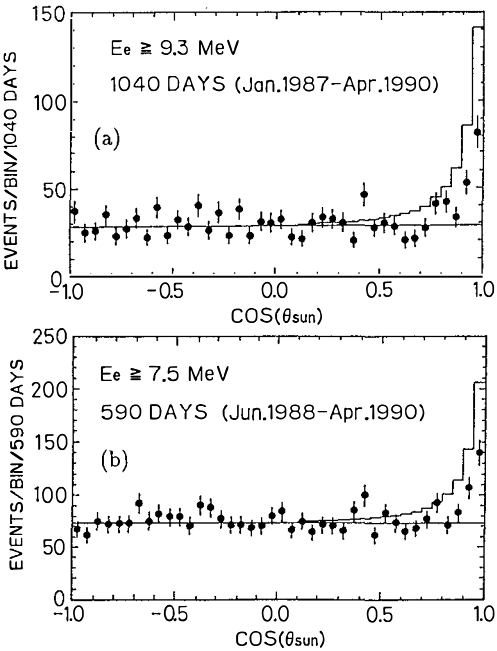

Figure 1. Angular distribution in $\cos\theta_{sun}$ of the 1040 days data sample with $E_e \geq$ 9.3 MeV, where θ_{sun} is the angle between the recol-electron direction and a radius vector from the Sun. The histogram drawn in this plot is the calculated signal distribution based on the SSM including the detector responce. (b)same as(a) but for later 590 days data sample with $E_e \geq$ 7.5 MeV.

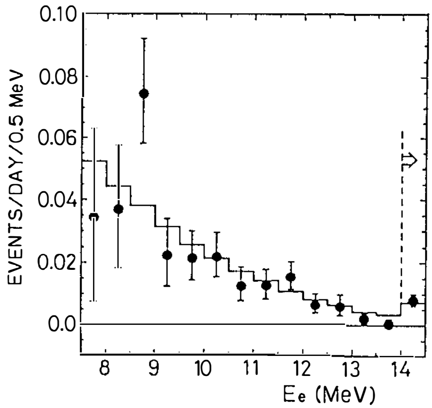

Figure 2. Differential energy distribution of recoil electrons, which is the energy distribution of the events in the fiducial mass after background subtraction. The histogram is 46% of the expected distribution from the SSM, which is the best fit to our data.

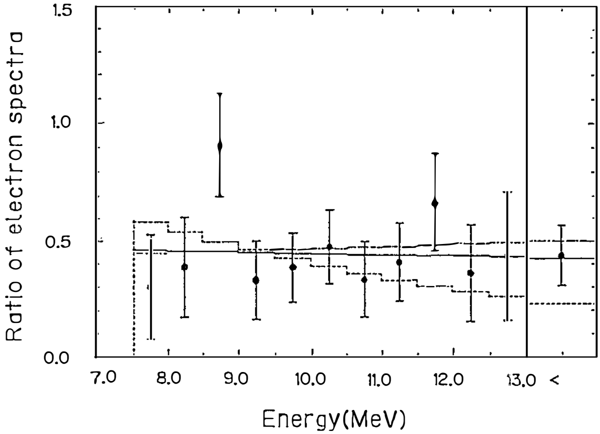

Figure 3.Comparison of differential energy spectrum with expected flux from the predictions. The plots are the ratio of observed differential energy pectrum to the expected spectrum. The lines are the distorted electron spectra due to neutrino oscillations with parameters ($\sin^2 2\theta$, Δm^2):(6.3×10^{-1}, 10^{-4}) for the solid, (10^{-2}, 3.2×10^{-6}) for the dash-dotted, and (2×10^{-1}, 1.4×10^{-4}) for the dashed lines.

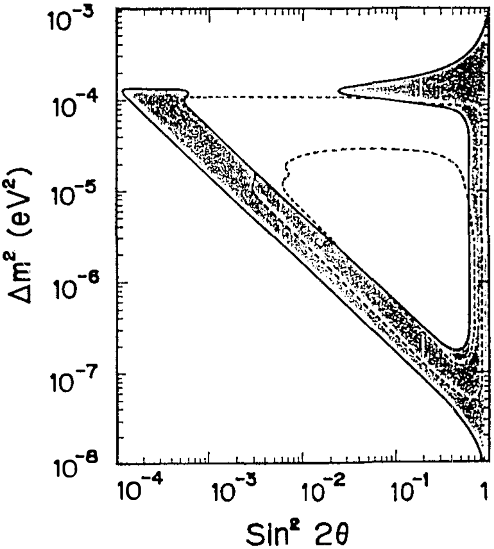

Figure 4.90% C.L. allowed region of the MSW solution for the Kamiokande-II(solid line) and the ^{37}Cl result (dotted lne). The theoretical neutrino production rate is taken from the SSM.

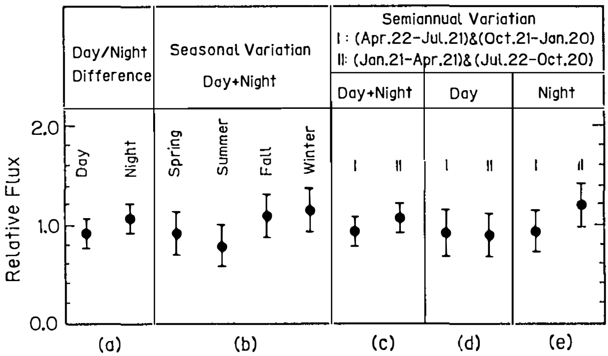

Figure 5.Measured solar neutrino fluxes relative to the averaged value(0.46 realtive to the SSM predicion); (a) daytime, nighttime; (b) spring, summer, fall, winter; (c) periods I and II (see text); (d) periods I and II, daytime; (e) periods I and II, nighttime.

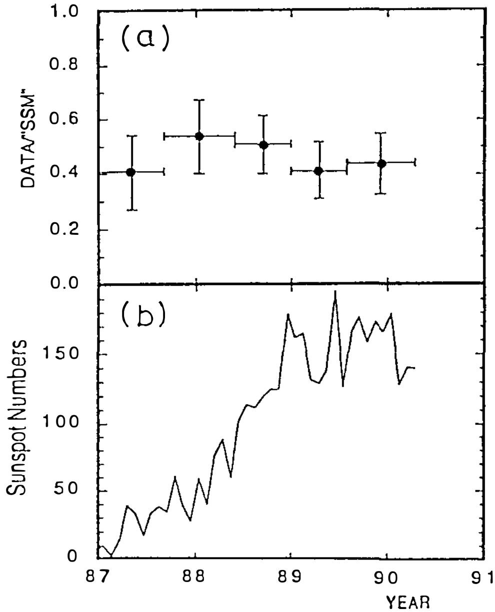

Figure 6.(a)Time variation of ^{8}B solar neutrino signal in the Kamiokande-II in the period from Jan. 1987 to Apr. 1990. Threshold for the two eariler pointes is $E_e \geq 9.3$ MeV, while for the three later points $E_e \geq 7.5$ MeV. (b)Time variation of sunspot number in the same period.