RECENT SUPER-KAMIOKANDE RESULTS ON SOLAR NEUTRINOS

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Abstract

The results of 800 days of solar neutrino measurement in Super-Kamiokande is presented. The precise measurement of the solar neutrino energy spectrum is one of the most important issue to understand neutrino oscillations. In order to measure the spectrum, it is very important to precisely determine the energy scale of the detector. For this purpose, we have used an electron LINAC. It can reduce the energy scale uncertainty less than ±0.5%.
Neutrino oscillations are essentially energy dependent phenomena. Actually different solar neutrino oscillation solutions require the different energy dependence. In addition, some solutions cause the day-night flux differences. Such measurements are independent of absolute flux results of solar models. Therefore an observation of the deviation from the expected energy spectrum and day-night flux differences not only show a definite evidence of the solar neutrino oscillation, but also differentiate possible oscillation solutions.
The results of the extensive analysis on neutrino oscillation is presented.

1 Introduction

1.1 Super-Kamiokande

Super-Kamiokande is a 50000 tons of ring imaging water Cherenkov detector, and it is located 1000m underground (2700m of water equivalent), to shield against cosmic ray muons, in the Kamioka mine in Gifu Prefecture, Japan. Cherenkov lights generated by charged particles scattered by neutrinos in water are detected by 11146 20-inch photomultiplier tubes. The experiment started normal data taking from April 1st in 1996. In this paper, the results of about 800days of data, which is from May in 1996 to April in 1999, are reported.

1.2 Solar neutrinos

The origin of the energy in the sun is the following nuclear fusion reaction which generates two neutrinos,

$$4p \rightarrow \alpha + 2e^{+} + 2\nu_e \tag{1}$$

The neutrino fluxes and spectra in these reactions are predicted by so called Standard Solar Models (SSMs) 1). The results of several solar neutrino experiments up to now are reported 2). Compared to the prediction of SSMs, the flux observed by all of the independent solar neutrino experiments are significantly small. This is called "solar neutrino problem". Various explanations of the solar neutrino problem have been proposed, and the most possible explanation is assuming neutrino oscillations 3). The most effective method to solve the problem is an independent measurement on solar models, because SSMs have been improved but the flux calculation from SSMs has remained ambiguous. Super-Kamiokande can measure the energy spectrum and the time dependence of the solar neutrino flux, (day/night or seasonal differences), and these are solar model independent measurements. Therefore, Super-Kamiokande is expected to provide definitive evidence of any possible new neutrino physics independent of the uncertainties in the solar models.

2 Detection method and energy calibration in Super-Kamiokande

For solar neutrino observation in Super-Kamiokande, recoil electrons through the following reaction are measured;

$$\nu + e^{-} \rightarrow \nu + e^{-} \tag{2}$$

The direction of recoil electrons has strong peak to the direction of original neutrinos, so we can identify solar neutrino signal. As the detector calibration, we use mono-chromatic electron sources from a linear accelerator (LINAC calibration). The incident electron energy from LINAC is determined by germanium detector with less than 20keV $^{4)}$. For the solar neutrino analysis, it is especially important that the uncertainty of absolute energy scale is reduced. We have done the energy calibration at several energy points (from 4MeV to 17MeV which fit the energy range of solar neutrinos) and several positions. Fig.1 shows the energy and position dependence of absolute energy scale obtained by the differences between the LINAC data and the Monte Carlo. The energy dependence of the difference is ±0.3% at 6MeV and ±0.1% at 11MeV. And the position dependence leads ±0.5% systematic error in an extrapolation of the energy scale determined at eight positions to the entire fiducial volume.

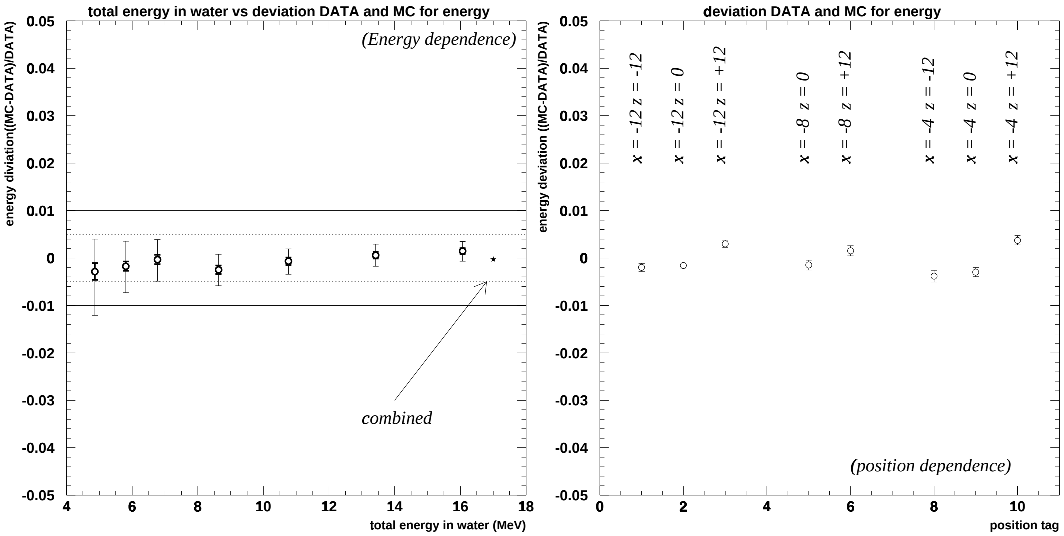

Figure 1: *Energy(left) and position(right) dependence of absolute energy scale obtained by LINAC data and M.C..*

3 Results and implications of solar neutrinos in Super-Kamiokande

3.1 Flux only analysis

We have obtained 825 days of data between 31 May 1996 and 3 April 1999, whose energy threshold is 6.5MeV. The observed solar neutrino flux in Super-Kamiokande is

$$2.45 \quad ^{+0.04}_{-0.04}(stat.) \quad ^{+0.07}_{-0.07}(sys.) \quad [\times 10^6/cm^2/sec]. \tag{3}$$

Comparing the result to SSM (BP98),

$$\frac{Data}{SSM} = 0.475 \quad {}^{+0.008}_{-0.007}(stat.) \quad {}^{+0.013}_{-0.013}(sys.), \tag{4}$$

the observed flux is significantly smaller than predicted flux. The solar neutrino flux observed by all four experiments can make allowed parameter region of neutrino oscillation as shown in fig.2. In MSW parameter region, we call three solutions "small angle solution", "large angle solution", and "LOW solution". In addition, the results also suggest some solutions around vacuum oscillation regions, which called "just-so solution". The calculation of the flux only analysis consider the theoretical uncertainties from SSM 5).

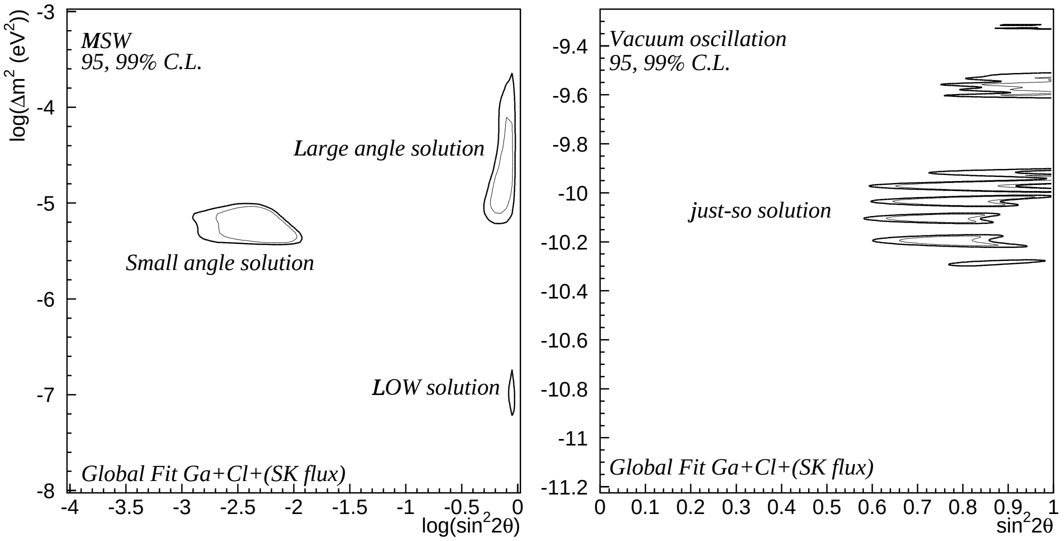

Figure 2: *Allowed region of neutrino oscillation parameter obtained by the combined result of observed solar neutrino fluxes from four experiments. The left figure shows the MSW region, and the right one shows the vacuum oscillation region.*

3.2 Day/Night flux differences

The day-night flux differences are also observed, and the result is,

$$\frac{\phi_{day} - \phi_{night}}{(\phi_{day} + \phi_{night})/2} = -0.065 \pm 0.031(stat.) \pm 0.013(sys.), \tag{5}$$

the night-time flux is 6.5% larger than daytime flux, but still have large errors. And fig.3(a) shows shows the solar neutrino flux in the daytime and the five night-time bins. The MSW effect through the earth, which is ν_e regeneration, causes flux difference between daytime and night-time, and the flux ratio depends on distances through the earth and the different electron density. Fig.3(a) also shows the expected solar neutrino flux in each bin assuming the two typical MSW parameters, corresponding to large and small angle solutions. In the large angle region, the flux difference of daytime and average night-time is larger than in small angle region. The solar neutrino flux differences in the daytime and night-time can restrict the some MSW parameter regions. Fig.3(b) shows the excluded regions from this analysis. The some parts of the allowed region from flux only analysis are excluded.

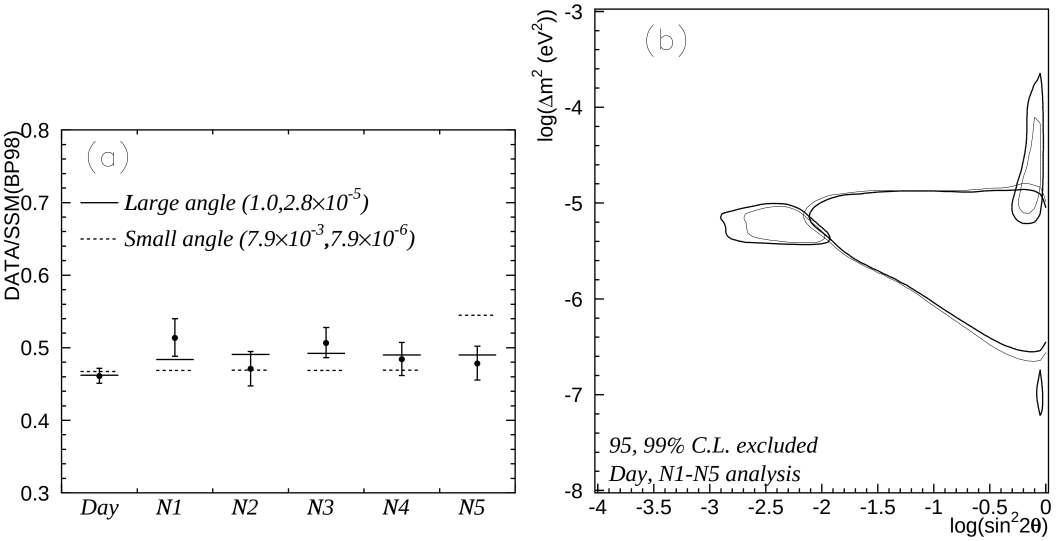

Figure 3: *(a) Flux diveded by daytime and five night time bins. The solid and dashed line shows expected flux assuming some neutrino oscillation parameters which are* $(\sin^2 2\theta = 1.0, \Delta m^2 = 2.8 \times 10^{-5}\ eV^2)$ *and* $(\sin^2 2\theta = 7.9 \times 10^{-3}, \Delta m^2 = 7.9 \times 10^{-6}\ eV^2)$*, respectively. (b) Excluded region of neutrino oscillation parameter obtained from fluxes of above six bins.*

3.3 Energy spectrum

Since May 1997, we have had new trigger scheme, which corresponds to 524 days of data, in order to obtain lower energy events. Due to this new trigger scheme, we have achieved the analysis energy threshold down to 5.5MeV. Fig.4 shows the observed spectrum of solar neutrino events normalized by the predicted energy spectrum. "SLE" which is shown in the figure means the newly analyzed lower energy range.

The chi-square for flat distribution is $\chi^2/\nu = 24.3/17$. (11.2% C.L.) In this figure, the spectrum assuming the several couples of neutrino oscillation parameters are also shown. The best fit parameters of neutrino oscillations are obtained at $(\sin^2 2\theta = 0.79, \Delta m^2 = 4.3 \times 10^{-10}$ eV^2) and it gives χ^2 of 17.3 with 17 d.o.f. (43 % CL).

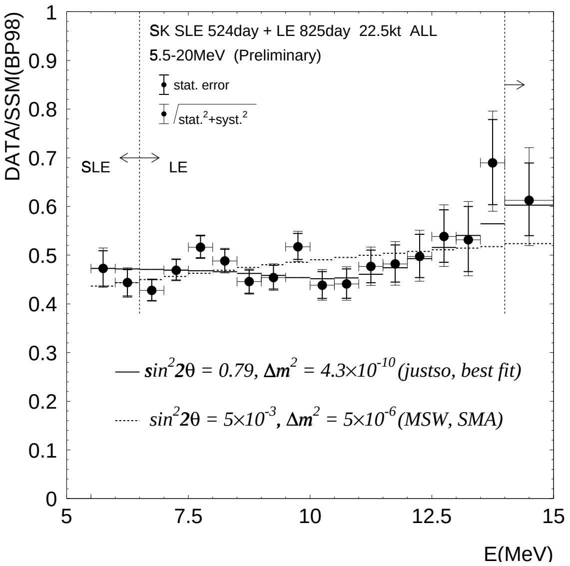

Figure 4: *Energy spectrum of solar neutrino events normalized by the predicted energy spectrum. The solid line shows the best fit value of the neutrino oscillation parameters which are* $(\sin^2 2\theta = 0.79, \Delta m^2 = 4.3 \times 10^{-10}$ *eV*^{2}*). The dashed line show a typical small angle solution* $(\sin^2 2\theta = 5 \times 10^{-3}, \Delta m^2 = 5 \times 10^{-6}$ *eV*^{2}*).*

It is suggested that the raise in higher energy bins of observed spectrum could be a contribution of a large amount of *hep* neutrinos, which is generated by $^3\mathrm{He} + p \rightarrow ^4\mathrm{He} + e^+ + \nu_e$ reaction in the center of the sun. The contribution of the *hep* neutrino flux at the higher energy region is only 1~2 %. However, if we fit the observed energy spectrum with free *hep* neutrino flux, the best fit value of the *hep* flux would be ~16.7 times as much as the expectation from the SSM. Such large flux of *hep* neutrinos should be investigated in the nuclear physics point of view. Whereas the statistics of solar neutrino events in higher region are still poor, so the *hep* flux will be able to extract by the spectral shape with enough statistics in future.

From the shape of energy spectrum and day-night differences observed in Super-Kamiokande, the excluded regions of neutrino oscillation parameters are obtained. Fig.5 shows the excluded region which is overlaied with the allowed region obtained by the result of the flux only analysis. The figure shows upper part of the "small angle solution" and upper and lower part of the "large angle solution" are excluded with 99% C.L.. Meanwhile, large part of the "just-so solution" is also excluded. Now we have only excluded region at 99% C.L., however, the increase of statistics especially around the higher energy region and lowering the energy threshold will enable us to make sure a possible solution of neutrino oscillation in near future.

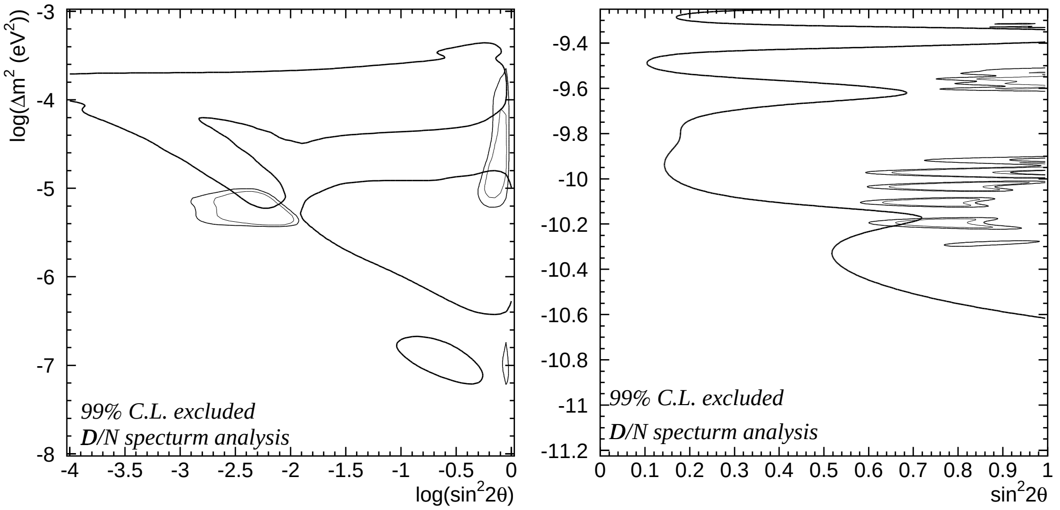

Figure 5: *Excluded region of neutrino oscillation parameter obtained from the shape of the day-night energy spectrum. The left figure shows the MSW region, and the right one shows the vacuum oscillation region.*

4 Conclusions

First of all, we achieved that the total systematic error coming from the energy scale has been less than ±0.5% using LINAC calibration. The solar neutrino spectrum is observed in 825 days of data above 6.5MeV and 524 days of data above 5.5MeV. We have found some hints from the day-night flux differences and energy spectrum. The flux differences between daytime and night-time are about 6.5%. The comparison of the spectral shape between observation and expectation gives a chi-square of 24.3 with 17 d.o.f. (11.2 % C.L.). In near future, the increase of statistics especially higher energy region and lowering the energy threshold will enable us to make sure a possible solution of neutrino oscillation.

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