Solar neutrinos results and oscillation analysis from Super-Kamiokande

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Abstract

The results of the solar neutrino spectrum measurement in Super-Kamiokande is presented. The precise measurement of the solar neutrino enegy spectrum is one of the most important key issue to understand neutrino oscillations. In order to measure the spectrum, it is very important to precisely determin the energy scale of the detector. For this purpose, we have used an electron LINAC. This calibration can be done at several positions, directions and energy points, and it can reduce the systematic errors of energy scale less than 1%.
Neutrino oscillations are essentially energy dependent phenomena. Actually different solar neutrino oscillation solutions require the different energy dependece. In addition, such a measurement is independent the absolute flux results of solar models. Therefore an observation of the deviation from the expected energy spectrum not only show the definit evidence of the solar neutrino oscillation, but also differenciate the possible oscillation solutions.
The results of the extensive analysis on neutrino oscillation is presented.

1 Introduction:

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). (Bahcall, Basu & Pinsonneault 1998)

The results of several solar neutrino experiments up to now are reported. (Cleveland, et al. 1995, Anselmann, et al. 1995, Abdurashitov, et al. 1994, Kim, et al. 1999) Compared to the prediction of SSMs, the flux observed by all of the independent solar neutrino experiments are significantly small. This is called “the solar neutrino problem”. Various explanations of the solar neutrino problem have been proposed. One of them is the modification of the SSM, but it is suggested to be difficult to explain the results of all four experiments. Another possible explanation is assuming neutrino oscillations. (Mikheyev & Smirnov 1985, Wolfenstein 1978) The solar neutrino flux observed by all four experiments can make allowed parameter region of neutrino oscillation as shown in the hatched region in Fig 4. In MSW parameter region, we call two solutions “small angle solution” (left side) and “large angle solution” (right side).

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 Energy calibration in Super-Kamiokande:

In the observation of solar neutrinos in Super-Kamiokande (SK), recoil electrons through the following reaction are measured;

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

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. (Nakahata 1998) 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. The typical energy distribution of LINAC calibration data and Monte Carlo is shown in Fig 1, and we calculate the energy resolution from this kind of data as follows; 19% at 6MeV and 15% at 10MeV. Fig 2 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. Finally, we estimate the total systematic error for the energy scale as follows; 0.9% at 6MeV and 0.7% at 11MeV.

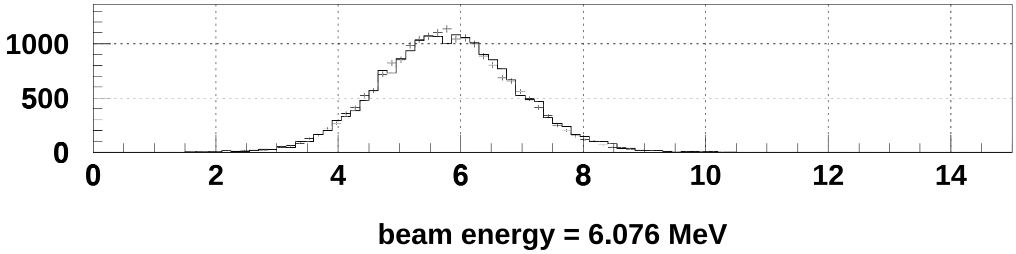

Figure 1: Typical energy distribution of LINAC(corsses) and M.C.(histogram) for $(x, z) = (-12m, +12m)$

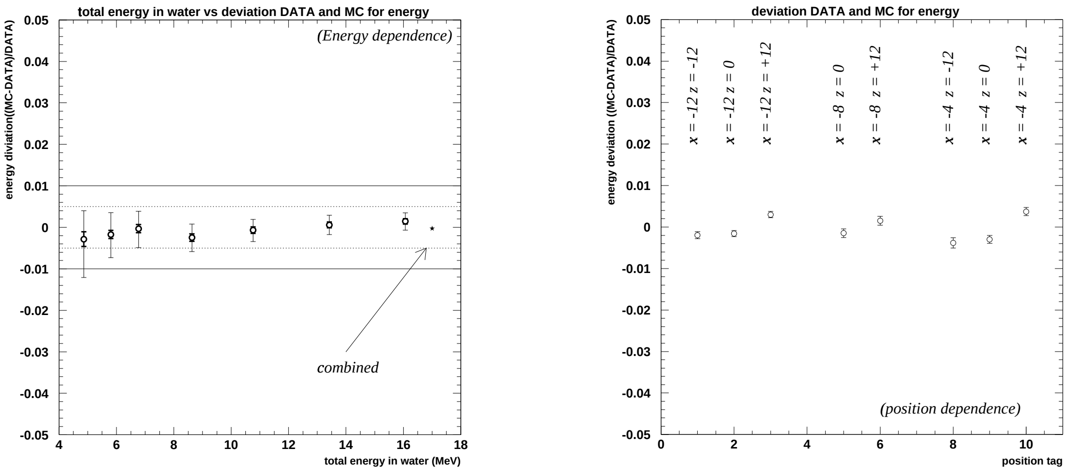

Figure 2: Energy and position dependence of absolute energy scale obtained by LINAC data and M.C..

3 Measurement of solar neutrino spectrum and the implications:

We have obtained 708 days of data between 31 May 1996 and November 1998, whose energy threshold is 6.5MeV. In addtion of that, we have had new triger scheme since May 1997, which corresponds to 419 days of data, in order to obtain lower energy events. Due to this new trigger scheme, SK has achieved the analysis energy threshold down to 5.5MeV. Fig 3 shows the 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 $\chi^2/\nu = 26.8/17$. (6.1% 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 ($\sin^2 2\theta = 0.85, \Delta m^2 = 4.3 \times 10^{-10}$ eV^2) and it gives χ^2 of 18.8 with 15 d.o.f. (22 % CL).

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 higer energy retion is only 1∼2 %. (The flux of *hep* neutrinos predicted by SSM is $2.1 \times 10^3/cm^2/sec.$) However, if we fit the observed energy spectrum with free *hep* neutrino flux, the best fit value of the *hep* flux would be ∼23±8 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.

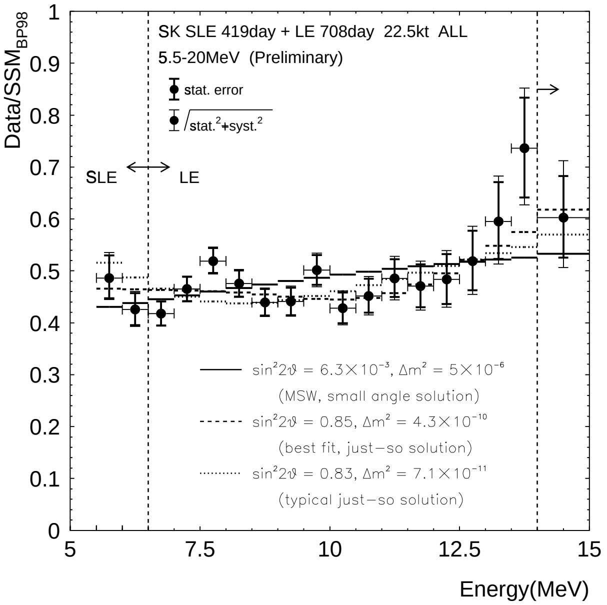

Figure 3: Energy spectrum of solar neutrino events normalized by the predicted energy spectrum. Inner and outer error bars shows the statistical and systematic errors, respectively. The dashed line shows the best fit value of the neutrino oscillation parameters which are ($\sin^2 2\theta = 0.93, \Delta m^2 = 4.2 \times 10^{-10}$ eV^2). The solid and dotted line show a typical small mixing angle solution ($\sin^2 2\theta = 5 \times 10^{-3}, \Delta m^2 = 5 \times 10^{-6}$ eV^2) and a just-so solution ($\sin^2 2\theta = 0.85, \Delta m^2 = 4.3 \times 10^{-10}$ eV^2), respectively. ($\nu_e \rightarrow \nu_\mu(\nu_\tau)$ oscillations are assumed here.)

From the shape of energy spectrum observed in SK, the excluded regions of neutrino oscillation parameters are obtained. Fig 4 shows the excluded region which is overlayed with the allowed region obtained by the combined result of measured solar neutrino flux from the several experiments. (SK, Chlorine, and Gallium experiment) 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 retion at 99% C.L., however, the inclrease of statistics expecillaly 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.

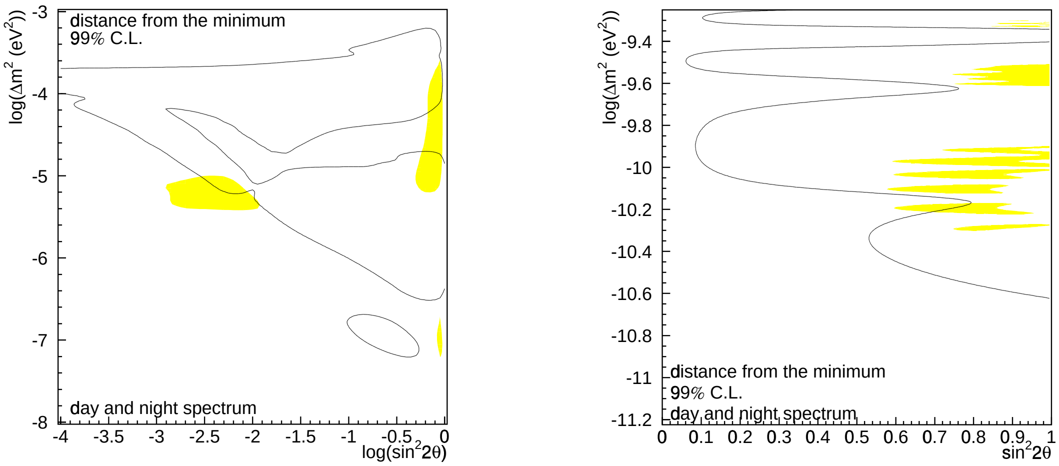

Figure 4: Excluded region of neutrino oscillation parameter obtained by the shape of the energy spectrum at 99%C.L.. The left figure shows the msw region, and the right one shows the just-so region. The hatched region show the allowed region obtained by the combined result of measured solar neutrino flux from the several experiments. (SK, Chlorine, and Gallium experiment)

4 Conclusions:

First of all, we achieved that the total systematic error coming from the energy scale has been less than 1% using LINAC calibration. The solar neutrino spectrum is observed in 708 days of data above 6.5MeV and 419 days of data above 5.5MeV. The comparison of the spectral shape between observation and expectation gives a chi-square of 26.8 with 17 d.o.f.(6.1 % C.L.). From the results of this spectrum, we can obtain the excluded region of neutrino oscillation with 99% 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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