FIRST RESULTS FROM SUPER-KAMIOKANDE

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A 50,000 ton water Čerenkov detector, Super-Kamiokande, has been operational since April 1996. Observation is currently being made with the threshold total-energy of 5.6 MeV. Data taken for 102 days have been analyzed and the preliminary results on solar neutrinos were obtained. Based on the data with visible energies $E_{vis} > 7\,\mathrm{MeV}$, the ^{8}B neutrino flux was $2.51 \pm^{0.14}_{0.13} \pm 0.18 \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. The data were divided in daytime and nighttime. The day and night fluxes agreed within statistical errors.

1 Introduction

Neutrinos are elusive and still mysterious particles. They interact only by weak forces and thus possess an enormous punch-through capability. Neutrinos are copiously produced in the core of a star by weak nuclear processes which are the source of energy and luminosity. Most of the neutrinos have energies less than 1 MeV but a small fraction of them are emitted with energies as large as 15 MeV by β-decay of rarely produced ^{8}B nuclei (half life 0.77 s).

The Sun is the star nearest to us and is indeed the only main-sequence star that can be seen with neutrino detectors. Since R. Davis had pioneered his work, the four experiments, Homestake, Kamiokande, SAGE and GALLEX [1], successfully observed the solar neutrinos, whose energies ranged from 0.23 MeV to 15 MeV. Their results thus confirmed that the Sun and in general the stars generate energies by nuclear processes. However, when comparison was made quantitatively, their results strongly disagreed with what the standard solar model (SSM) predicts. In fact the Homestake, Kamiokande, SAGE and GALLEX experiments observed only 30 % ($E_\nu > 0.814\,\mathrm{MeV}$), 50 % ($E_\nu > 6.5\,\mathrm{MeV}$), 50 % ($E_\nu > 0.233\,\mathrm{MeV}$) and 50 % ($E_\nu > 0.233\,\mathrm{MeV}$) of the expected yields [2], respectively. It is of utmost importance to find what causes such large discrepancies.

The supernova is another astronomical object that is visible with neutrinos though its occurrence is very rare. The supernova SN1987A in the Large Magellanic Cloud (LMC) went off in February 1987 and the underground detectors, notably Kamiokande and IMB [3], recorded neutrino bursts and confirmed the basic process underlying the explosion of type II supernovae, namely gravitational collapse of the central iron core. However the observed number of events (11 in Kamiokande and 8 in IMB) were frustratingly few and did not allow us to study in detail the explosion mechanism of the supernova.

Successful observations of solar and supernova neutrinos motivated us to construct a new neutrino detector, Super-Kamiokande, much larger than the current underground detectors which, compared with other nuclear and particle experiments, are already extremely massive. Super-Kamiokande began its operation in April 1996.

The Super-Kamiokande experiment studies not only astrophysical neutrinos but also atmospheric neutrinos. It has been known for some time that the ratio of observed μ to e in $E_{vis} \leq 1\,\mathrm{GeV}$ which are produced by atmospheric neutrinos is about 40 % lower than what one naively expects[4]. The ratio μ/e is closely related to $(\nu_\mu + \overline{\nu_\mu})/(\nu_e + \overline{\nu_e})$ and theoretical uncertainties such as the primary cosmic-ray flux largely cancel. Hence the small μ/e ratio, if the results are indeed true, provides strong evidence for neutrino oscillations of $\nu_\mu \rightarrow \nu_e,\ \ \nu_\tau$ or ν_s (sterile neutrinos). It is of utmost importance to confirm this atmospheric-neutrino anomaly with the Super-Kamiokande detector.

2 Super-Kamiokande Detector

The Super-Kamiokande detector is a 50,000 ton water Čerenkov detector located 1,000 m underground in the Kamioka zinc mine and about 150 m south of the old Kamiokande facility. The excavation of a 65,000 m^3 cavity began in December 1991 and ended in June 1994. Lining of the cavity with stainless-steel plates followed and a huge water tank of $39.3\,\mathrm{m}\phi \times 42\,\mathrm{m}h$ was completed in April 1995. It then took till December 1995 to mount 11,200 photomultiplier tubes (PMT) of $50\,\mathrm{cm}\phi$ in the inner detector and 1,800 PMTs of $20\,\mathrm{cm}\phi$ in the outer detector. The tank was completely filled with pure water by the end of March 1996 and the observation started in 1 April 1996 as originally scheduled.

The detector consists of the inner and outer parts. The outer one serves as a veto counter for incoming cosmic-ray muons as well as a shield layer against γ-rays and neutrons coming from the rock. The inner detector is the central 32,000 ton of water mass viewed by 11,200 PMTs and is completely surrounded by the outer detector with a water layer of about 2.7 m thick. It is this inner part that detects interactions of solar and atmospheric neutrinos and hopefully supernova neutrinos in near future.

50,000 ton of water contained in the inner and outer detectors is continuously purified by means of de-ionization, fine filtering and degasification. Water must be free of natural-radioactive elements, especially ^{222}Rn whose daughter nuclei ^{214}Bi β-decay and emit electrons of kinetic energy $T \leq 3.3\,\mathrm{MeV}$. Due to a finite energy resolution of the detector these electrons occasionally output signals equivalent to $E_{vis} \geq 6\,\mathrm{MeV}$ (E_{vis} is the visible energy and equivalent to the electron *total*-energy) and hence are significant background to the solar-neutrino observation. Water should be transparent in order for Čerenkov photons to traverse on average 20 m of water and to reach PMTs on the wall without substantial losses. Rn concentration and water transparency have been monitored continuously and the current levels (as of October 1996) are less than 5 mBq/m^3 and 55 m for Rn concentration and average absorption length of Čerenkov light, respectively.

PMT signals are fed into ADC/TDC circuits of double-hit capability through 70 m coax-cables. The circuits are capable of recording double pulses with a minimum separation of 1 μs and thus are able to efficiently detect electrons from μ- decay. The data-acquisition system as well as the electronics were specially designed to cope with burst events of more than 40 kHz so that Super-Kamiokande should be kept alive in case of near-by supernovae.

Gain factors of all the PMTs were set to 10^7 and their variations measured within 7 % by means of a Xe-lamp system. The timing resolution is typically 2.9 ns r.m.s. at one photoelectron (p.e.) level.

3 Calibration

The Super-Kamiokande detector must be calibrated periodically to update the basic parameters, the most important of which are the energy estimator (ratio of the number of hit PMTs in the time interval of 50 ns to the deposited energy with corrections of water transparency and PMT photosensitive area) and the resolutions of position and angle determinations. To experimentally determine these parameters we have been using γ-rays of about 9 MeV emitted from Ni(n,γ)Ni reactions. The γ-source consists of a polyethylene vessel (19 cm $\phi\times$ 20 cm$h$) and 2.8 kg of Ni threads. A ^{252}Cf neutron source is placed at its center. The vessel is lowered at a predetermined position in the water. Water embeds the vessel when it descends and thermalizes the neutrons. The calibration with the Ni-γ system has been carried out on average every two weeks. The energy estimator was found to be stable with an accuracy better than 1 %.

Recently the calibration with a low-energy electron beam has been successfully carried out. A small electron linear accelerator (LINAC) was installed in a tunnel near the Super-Kamiokande cavity. The electron beam of energies between 5 MeV and 16 MeV were transported in a magnetically-shielded vacuum pipe, bent by 90 deg downward and shot in the water through a 30 m vacuum pipe. At the exit window a thin plastic scintillation counter was placed and its signals were used to initiate the data-taking. The first calibration was carried out at the coordinate (-1237, -70.7, 1206) cm where (0,0,0) corresponds to the detector center. The data analysis then followed in exactly the same way as for the real data. Figure 1 shows the E_{vis} distributions for four electron energies of 5.866, 6.782, 8.637 and 15.966 MeV , where E_{vis} is expressed as the effective number of hit PMTs . They were found to agree with the Monte Carlo simulation within an accuracy of 1 %. The beam position was also successfully reconstructed. The systematic shift of the reconstructed position at 8.6 MeV, for example, was less than 10 cm and the resolution was about 60 cm and 35 cm for the longitudinal and transverse directions to the beam, respectively. The beam direction was also reconstructed and reproduced very well by the Monte Carlo simulation. Though the calibration results are still preliminary, we believe that the detector characteristics are well understood to perform the detailed study of solar neutrinos.

The trigger of the Super-Kamiokande detector is made by simply counting the number of hit PMTs within a gate time of 200 ns. Its efficiency was determined with the LINAC calibration system, which is shown in Fig.2 .

4 First Results on Solar Neutrinos

Low-energy data accumulated during 101.9 day of live-time have been analyzed for solar neutrinos. Preliminary results will be presented here.

The basic reaction for detecting solar neutrinos is neutrino-electron elastic scattering, $\nu_e + e \rightarrow \nu_e + e$. Its cross section is precisely known from electroweak theory. Elastic scattering by other neutrino species, $\nu_i + e \rightarrow \nu_i + e,\ i = \mu$ or τ also takes place but its cross section is six times lower. It is this recoil electron that emits Čerenkov light and is detected. The electron is scattered in the forward direction if the neutrino energy is much larger than the electron mass, which is the case for the present experiment. This forward peak was used to pick up solar-neutrino signals from the isotropic background.

The analysis approximately followed the following way which had been established in the old Kamiokande experiment:
(1) Eliminate obvious external noises such as electric noises (6.1×10^7 events left); (2) Eliminate low-energy events within 20μs after preceding muons to avoid contamination of electrons from μ-decay (5.5×10^7 events); (3) Space-reconstruct remaining low-energy events and determine the event positions and directions (4.7×10^7 events); (4) Estimate visible energies, E_{vis}, assuming events to be electrons; (5) Apply the fiducial-volume cut, namely pick up events within the central 22.5 kton of the inner detector to reduce incoming

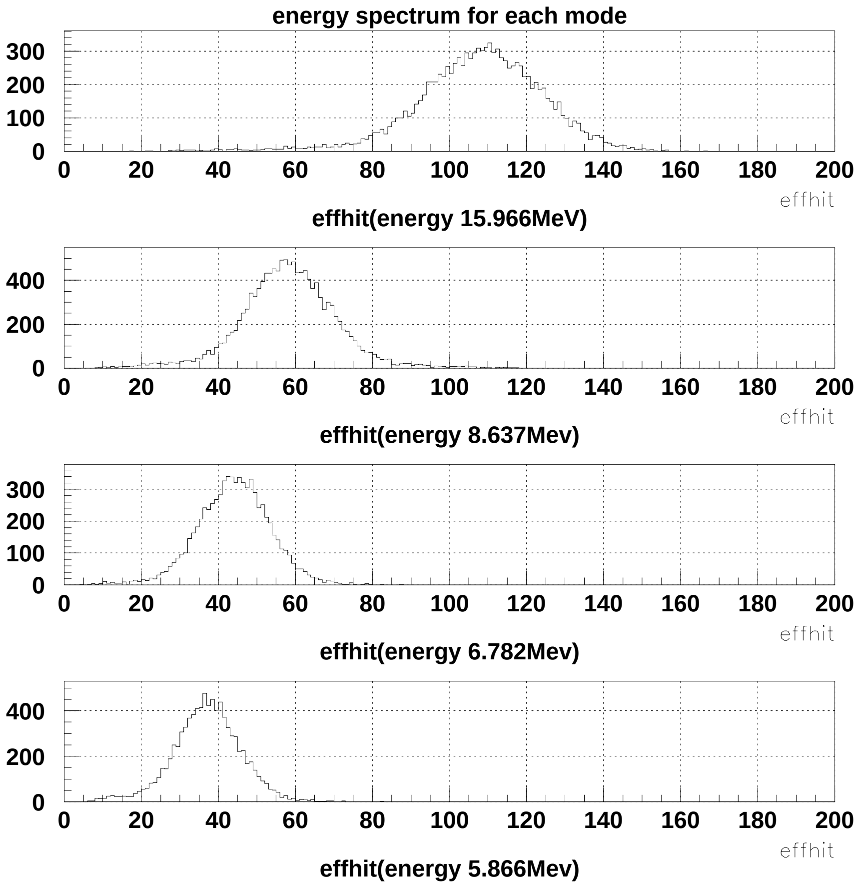

Figure 1: Distribution of the energy estimator (effective number of hit PMTs) for electrons of 5.866, 6.782, 8.637 and 15.966 MeV (preliminary).

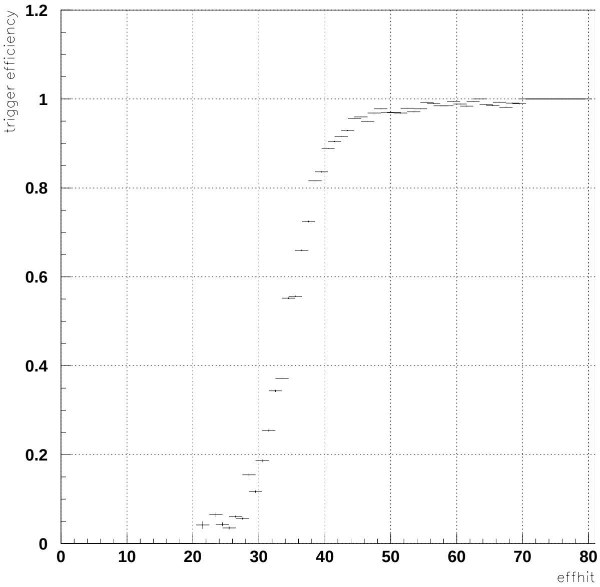

Figure 2: Trigger efficiency of the S-K detector at the position of the beam injection as a function of the effective number of hit PMTs, which is an energy estimator of electons. 35 hits correspond to electron tatal-energy of 5.51 MeV. This result was obtained with the LINAC calibration. Note the trigger efficiency slightly depends on event positions in the detector.

background γ-rays (4.2×10^6 events); (6) Pick up events with $7 \leq E_{vis} \leq 20\,\mathrm{MeV}$ (1.1×10^5 events); (7) Eliminate spallation products by cosmic-ray muons, by taking advantage of temporal and spacial correlations of low-energy event and preceding muons (1.4×10^4 events). Now the basic data sample is ready: (8) Make the $\cos\theta_{sun}$ distribution, where θ_{sun} is the directional correlation of the event with respect to the Sun, $\theta_{sun} = 0$ being the forward direction. Solar-neutrino events ought to be accumulated near $\cos\theta_{sun} = 1$: (9) Count the number of excess events near $\cos\theta_{sun} = 1$.

Figure 3 shows the resultant angular distribution for $E_{vis} \geq 7\,\mathrm{MeV}$. A forward peak is clearly visible above the flat background. The number of excess events in the peak is $1,005^{+55}_{-52}$. Based on this number, the total ^{8}B-neutrino flux is $2.51^{+0.14}_{-0.13} \pm 0.18 \times 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The systematic error will soon be reduced significantly thanks to the precise LINAC calibration. This result is quite consistent with what Kamiokande obtained over 2,000 days of live-time.

However the absolute flux value is not a main issue any more. What is

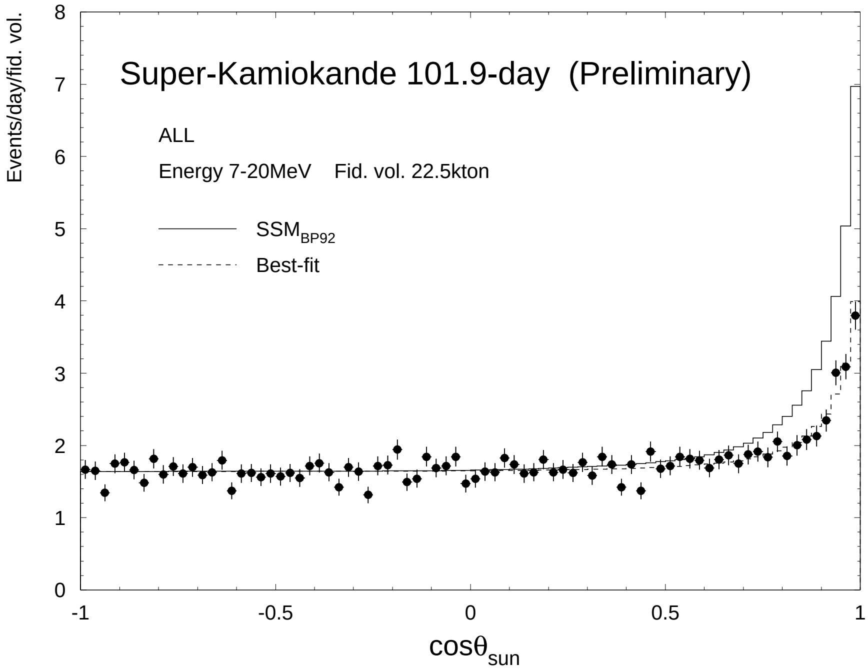

Figure 3: $\cos\theta_{sun}$ distribution for $E_{vis} > 7\,\mathrm{MeV}$ after fiducial-volume and spallation cuts. Excess events near the forward direction are signals produced by solar neutrinos. Data correspond to 101.9 day live-time.

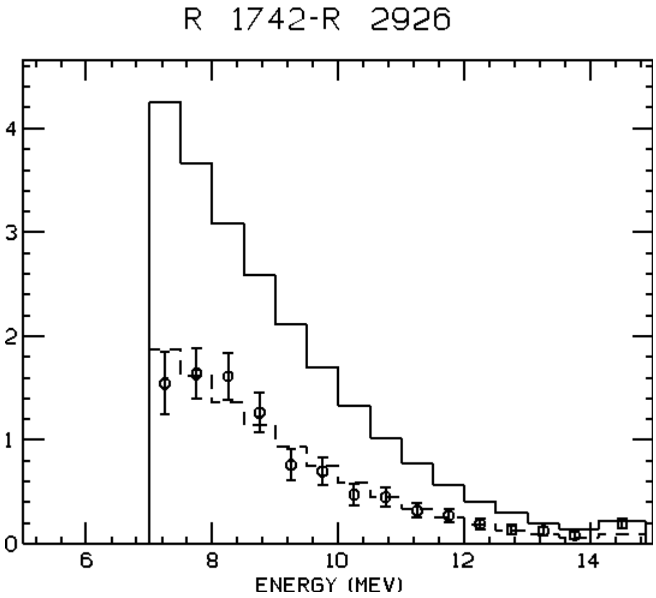

Figure 4: E_{vis} distribution of solar-neutrino events. The solid histogram is the prediction from Bahcall-Pinsonneault's theory[6], while the dashed one is the best fit with a scale factor of 0.441 to the theoretical prediction.

important is to find the true mechanism that causes the solar-neutrino problem. Super-Kamiokande intends to measure the precise shape of the ^{8}B neutrino spectrum independent of the absolute flux value. The data were binned by the visible energies, E_{vis} and the above procedures were repeated. Figure 4 shows the resultant spectrum together with the expected histogram. The shape itself agrees with the expectation within the statistical errors. Unfortunately the current statistics is not large enough to find a faint spectral distortion predicted by the small-angle solution of the MSW mechanism[5], which is thought to be one of the best candidate solutions to the solar-neutrino problem.

Another important measure is to study the difference in the ^{8}B neutrino fluxes between day and night. In fact the large-angle solution of the MSW mechanism[5] predicts a small excess in the nighttime which is caused by the regeneration of ν_e in the earth. We divided the data into day and night and analyzed them in the same way. The resultant ^{8}B neutrino fluxes are $2.30^{+0.18}_{-0.17} \pm 0.17 \times 10^6$ and $2.76^{+0.21}_{-0.20} \pm 0.20 \times 10^6$ cm^{-2}s^{-1} for day and night, respectively. We do not see the difference within the present statistical errors.

Note that the systematic errors of both fluxes are highly correlated and some of them cancel when the ratio of day/night is taken. We obviously need more data to confirm or disconfirm the large-angle solution.

5 More Work Needed

The Super-Kamiokande detector is working almost as good as we expected. Various calibrations such as water transparency, energy estimator, etc. are being conducted successfully. However we have not achieved one of the goals, namely the threshold energy of 5 MeV. Water purity reached a low enough level but there are still large background events below 7 MeV which prohibit further study of solar neutrinos down to 5 MeV. We are still working hard to find what is the origin of these events and hope to resolve the problem in near future.

We probably need two more years of observation to definitely see if the ^{8}B neutrino spectrum is really distorted or if the flux in the nighttime is indeed larger than in the daytime.

The online supernova (SN) watch has been installed and SN alarms are issued on average once every month, the rate of which is adjustable depending on the detection efficiency. No events remained until now after inspecting the spacial uniformity of the alarm events: They were clusters of spallation products by hard interactions of muons. Currently Super-Kamiokande is 100 % efficient to find SNs at a distance as far as 100 kpc. Obviously the detector must be running all the time as the SN neutrino burst lasts for only tens of seconds. The current data-taking efficiency is about 95 %. The loss is due to frequent calibration work. It may eventually reach $97 \sim 98$ % very soon.

The analysis of atmospheric neutrinos is going well and the first result will be presented in the summer this year with statistics several times larger than the total data obtained in Kamiokande.

In order to confirm the atmospheric-neutrino problem in a convincing way we will carry out the long-baseline neutrino-oscillation experiment between Super-Kamiokande and KEK from the beginning of 1999.

Proton decay is being and will be searched for as long as the Super-Kamiokande experiment continues, hopefully for more than 50 years. Our effort is especially focused on the decay mode $p \rightarrow \nu K^+$ which is predicted by the SUSY GUTs. In five years we will reach the sensitivity of 3×10^{33} years for this decay mode.

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