OBSERVATION OF SOLAR NEUTRINOS AND SEARCH FOR 'SOLAR-FLARE NEUTRINO' EVENTS IN KAMIOKANDE

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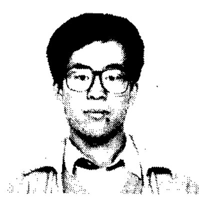

ABSTRACT

Solar-^{8}B-neutrinos were observed in the KAMIOKANDE-II detector. The preliminary result of the observed flux is 46% of the best estimate of the standard solar model ($\sim$30% 1σ error). This result is based on 450 days' data starting from January 1987 to May 1988 with electron energy threshold of 9.3 MeV.

A search has been made for the correlation between large solar flares and neutrino events observed in the KAMIOKANDE detector for the period of July 1983 $\sim$ July 1988. No significant neutrino signal was found at the time of a solar flare, giving a limit on the time-integrated "solar-flare ν_e" flux $< 3.7 \times 10^7$ (2.5×10^9) cm^{-2} per flare at 90 % confidence level for $E_\nu = 100$ (50) MeV.

[1]For the latter half of this report

Observation of Solar Neutrinos in KAMIOKANDE-II

The solar neutrino problem is an important issue in understanding the physics of the sun and possibly the fundamental physics. That is, the observed value of the solar neutrino flux in the chlorine experiment by Ray Davis *et al.*[1] is considerably lower than the predicted value based on the standard solar model.[2] This is a long-standing problem for two decades and a lot of suggestions to solve this discrepancy have been made. For example, modification of the standard solar model,[2] neutrino oscillation into other species,[3] neutrino magnetic moment[4] and so on. In any case the most important key to solve this problem is the independent observation of the solar neutrino flux. Followings are the preliminary result in Kamiokande, a large water Čerenkov detector situated 1000 meter underground in the Kamioka zinc mine in Japan.

The dominant basic process is the elastic scattering of electron neutrino on electrons. We observe scattered electrons by Čerenkov light. This method has some advantages: electrons keep some directionality, energy information from electrons is available, and real-time observation is possible.

By real-time observation, we can check the time variation of the solar neutrino flux such as day/night effect, seasonal variation and so on. This may help to make models to solve the solar neutrino problem.

The Kamiokande detector includes 948 photomultipliers of 20 inch diameter in the inner 3000-ton water tank and 123 photomultipliers of the same type in the anticounter.[5] The anticounter covers the inner counter completely and has a thickness of about 1.5 meters so as to reduce gamma-rays from the surrounding rocks. There are a lot of background sources which we should overcome to observe low energy events. Radioactivity in water and in air was severe. In order to reduce beta-rays from ^{214}Bi in water, we added ion-exchanger and uranium exchanger, and we made the detector airtight.

The charge and timing information of each photomultiplier is digitized in multi-buffered electronics and this is used to reconstruct the vertex, direction and energy of the event. The energy calibration is performed with gamma-rays of up to 9 MeV from the reaction Ni(n,γ)Ni, with electrons from muon decays, and with the beta-rays from spallation products of cosmic ray muons. These checks give the absolute energy uncertainty of less than 3 %. The vertex and angular resolution is estimated as 1.7 m and 28° respectively for an electron of 10 MeV including the multiple scattering effect. The number of hit photomultipliers is almost proportional to the electron energy (E_e), and we can estimate its energy with $22/\sqrt{E_e/10\,\mathrm{MeV}}$ % error. The trigger efficiency is 50% for 7.6 MeV electrons and 90 % for 10 MeV. The trigger threshold is lowered by 12 % since October 1987.

The search for solar neutrinos was carried out on the 450 days of data with relatively low radioactivity background which were taken from January 1987 to May 1988. The data sample is selected with the following criteria: (1) the total number of photoelectrons in the inner counter had to be less than 100, corresponding to 30 MeV electron; (2) the total number of photoelectrons in the anticounter had to be less than 30 ensuring event containment; (3) the time interval from the preceding event had to be longer than 100 μs, to exclude electrons from muon decays. Then we applied three cuts to reduce backgrounds.

One of them is a fiducial cut. Most of gamma-rays which came from the rock had vertex positions near the wall of the detector, and were rejected by limiting the fiducial volume of 680 tons, which is 2 m inside the barrel and bottom photomultiplier layers and 3.14 m inside the top layer.

Next we applied the spallation cut. Events were cut if they had small time gap from and spatial correlation with preceding muons, which are mostly accompanied with energetic showers. (For details see ref. 6.) The dead time due to this cut is 10.4 % and the efficiency is estimated as 90 %.

The last one is the remaining gamma-ray cut. Low energy gamma-rays are tend to inject the detector vertically to the tank surface. Events were rejected which had vertex positions near the edge of the fiducial volume (outer 1 m layer) and directions inward (cosine of the angle relative to the normal to the nearest wall > 0.67) relative to the nearest wall. This cut introduced an additional dead time of 13 %.

The event rate was reduced by these cuts as shown is Figure 1. This shows the integral energy spectrum of low energy data sample. The background is reduced by a factor of about 700, and the signal-to-noise ratio is about 1/7 for the ^{8}B neutrino flux predicted by the standard solar model. This signal-to-noise ratio is not enough to seperate solar neutrinos, but we have information on directions of scattered electrons so we tested the directional correlation of the event sample with the sun.

Figure 2 shows the typical distribution in $\cos\theta_{sun}$ for $E_e > 10.1$ MeV, where $\cos\theta_{sun} = 1$ corresponds to the expected direction of the sun. We see a clear enhancement toward the sun, but it is considerably smaller than the predicted value by the standard solar model.

The strength of the solar neutrino signal was calculated by fitting the $\cos\theta_{sun}$ distribution with a flat background plus an expected angular distribution of the signals. This was done for different energy ranges and resulting E_e spectrum is shown in Figure 3. Comparing this plot with the predicted one, we obtain a solar neutrino flux of 0.46 times the standard solar model prediction with about 30% (1σ) error. This is a preliminary result and the precise estimation of errors is under investigation.

Our result should be compared with the chlorine experiment. Combined data of the chlorine experiment since 1970 till 1987 gives (2.18$\pm$0.3) SNU or 0.28 times the standard solar model prediction, but recent 5 runs give a rather high rate of 5 SNU or 0.63 times the standard solar model prediction.[7] Our result does not seem to be inconsistent with the recent results from the chlorine experiment. Notice that we can observe only ^{8}B neutrinos while the chlorine experiment is expected to see not only ^{8}B neutrinos but also neutrinos from other origins, so direct comparison is not enough to evaluate both results.

Finally I mention the improvement in progress. Continuous observation may clarify the time variation of the solar neutrino flux, needless to say. Since June 1988 we raised the high voltages applied to photomultipliers so that the gain of photomultiplier is doubled. This improved the vertex and angular resolution in the event reconstruction and reduced the background rate by a factor of about three. This improved data is now under analysis to get a flux value and we expect better signal-to-noise ratio and more statistics by lowering the energy threshold for analysis. Another improvement is aimed to remove radon further from water and air. A cooled charcoal chamber and a more powerful degasser have been installed recently for this purpose.

In summary, we observed a clear signal of solar neutrinos. The flux value is 0.46 times the standard solar model prediction with about 30 % error, indicating the solar neutrino problem is still a puzzle.

Search for 'Solar-flare Neutrino' Events in KAMIOKANDE[7]

Ray Davis reported a possible correlation of the argon atom production rate in his chlorine detector with large solar flares.[8] The excess atoms observed in run number 27, 51 and 71 apparently coincides with the solar particle flux. The run number 86 is not associated with a large solar flare, but an intense gamma-ray burst occurred during that time and it might be the cause of the excess of argon atoms. If these excesses are really come from solar flare particles accelerated to high energies, our Kamiokande detector should catch many neutrino events within a few hours during a large solar flare,[1,9] if the energies of these neutrinos are in the 100 MeV region, as is expected from the calculation.[10]

Solar flares are ranked by *importance*. We picked up large solar flares with optical *importance* greater or equal to two or with soft X-ray importance X. There were 99 solar flare times since June 1983 till July 1988.[11] We also checked hard X-ray events and proton events. which were obserbed in a satellite orbit.[11]

General features of neutrino events observed in the Kamiokande are already reported[12]. We used two selected event samples. One is fully-contained events with selected momenta of 30 to 1330 MeV/c for electrons and 205 to 1500 MeV/c for muons. The fiducial mass for this analysis was 880, 780 and 1040 tons for 6 July 1983 $\sim$ 3 October 1984 (live time 342 days), 29 December 1984 $\sim$ 9 November 1985 (222 days) and 21 November 1985 $\sim$ 14 July 1988 (750 days). We have 326 events in the total exposure of 3.44 kiloton years. 225 of such events had only one Čerenkov ring. 122 of them were assigned to be electron-like ($e^{\pm}$, γ) events and others were muon-like ($\mu^{\pm}$, $\pi^{\pm}$) events. Another dataset is the low energy samples with reduced backgrounds (recoil electron momentum 19$\sim$50 MeV, fiducial mass 680 tons). Only one electron-like event was found during the period from 3 December 1986 to 4 July 1988.

We searched possible solar-flare neutrino candidates among these events. Only one muon-like event was found during flares with *importance* greater or equal to three. This is statistically consistent with the background level of 0.35 event. When we extend the analysis to flares with *importance* greater or equal to two, two events are within the nominal duration of 99 flares. These are both muon-like single-ring events. Taking the extended interval from one hour before the start of the flare to one hour after the end, one muon-like single-ring event and two multi-ring events are added to the candidate list. The low energy event happened far from the flare duration. During 11 hard X-ray events and 15 proton events, we have no candidates so far.

If a large solar flare arise on the side opposite to Earth, we cannot see it by the optical observation. However, neutrinos may come through the solar body. In such a case we cannot define a coincidence, but we expect such 'invisible' flares happen more often when we observe solar flares successively. So we look for the correlation between the numbers of flares and neutrino events summed over long periods. Considering the statistics of our neutrino events, we plot monthly numbers for flares, hard X-ray and proton events, and neutrino events in Figure 4. The solar neutrino flux measured in the chlorine experiment is also shown in the same figure. We see no apparent correlation.

During the period of the run numnber 86 of the chlorine experiment, there was a gamma-ray burst observed by the SMM satellite.[13] If the 40 excess argon atoms seen in the chlorine experiment was caused by this burst, the Kamiokande should observe about 3600 events if the neutrino energies are 100 MeV. However, we observed no neutrino event. There were two electron-like events and two muon-like events in the whole period of the run number 86. These are consistent with the random distribution of neutrino events. Therefore, we may conclude the excess capture of the run number 86 of the chlorine experiment was at least not due to the neutrino flux with an energy in excess of 50 MeV.

Figure 5 shows the comparison of the sensitivity of the Kamiokande and the chlorine experiment. The shaded region indicates the solar flare electron neutrino flux estimated from the results of the chlorine experiment. To draw the sensitivity curve we considered two cases: one is only for ν_e and the other for $\nu_e : \overline{\nu}_e : \nu_\mu : \overline{\nu}_\mu = 1:1:2:2$. When we do not know neutrino composition, the flux limit derived from the former is regarded as a conservative limit. We can set a 90 % confidence level upper limit of 3.7×10^7 (2.5×10^9) cm^{-2} at $E_\nu = 100(50)$ MeV per flare to time integrated electron neutrino flux, which is considerably lowerer than the estimated flux especially in the energy region greater than 50 MeV.

In conclusion, we found no significant correlation of our neutrino events with solar flares. Our upper limit is 2000 times smaller than the estimated flux deduced from the excess argon atoms observed in the chlorine experiment. Nevertheless, the next solar maximum will come in 1990 ± 1 year, and the possibility to detect solar flare neutrinos from even greater flares remains to be explored.

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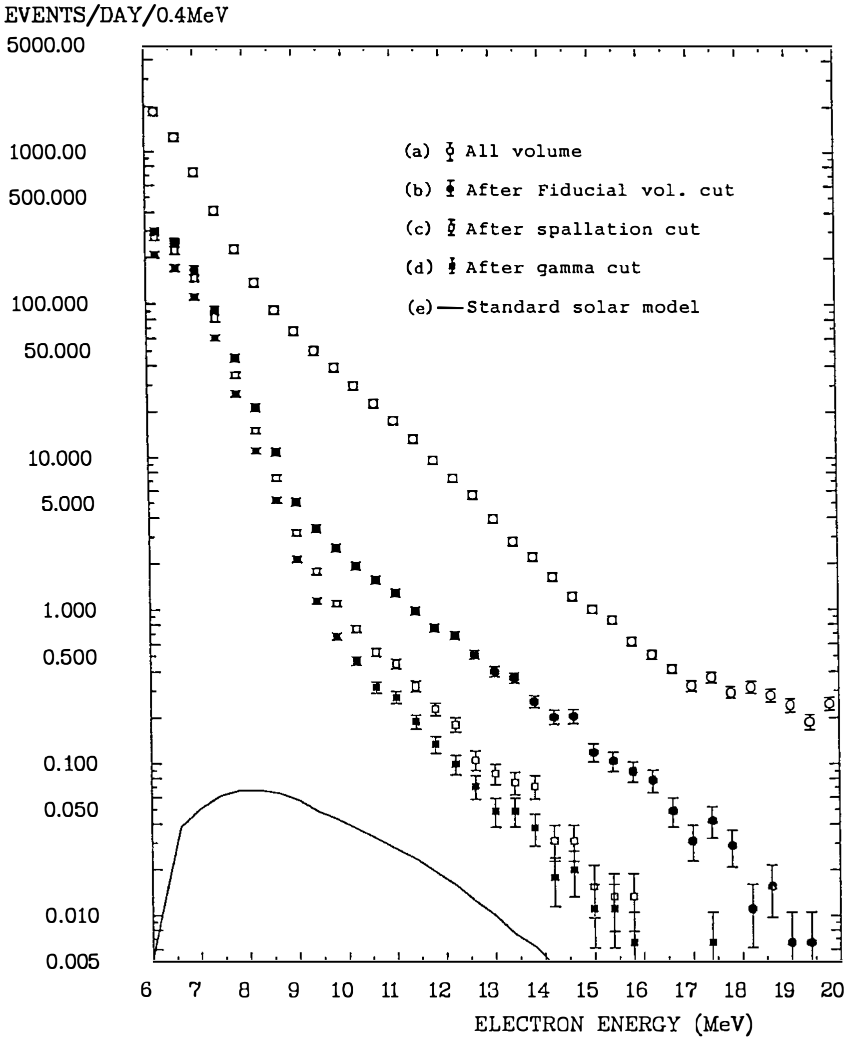

Figure 1. (a) Differential energy distribution of low energy events in the total mass of 2140 tons. (b) Same as (a) but fiducial mass of 680 metric tons used in the solar neutrino analysis. (c) Same as (b) but after the spallation cut. (d) Same as (c) but after the gamma-ray cut. (e) Monte Carlo prediction of the standard solar model.

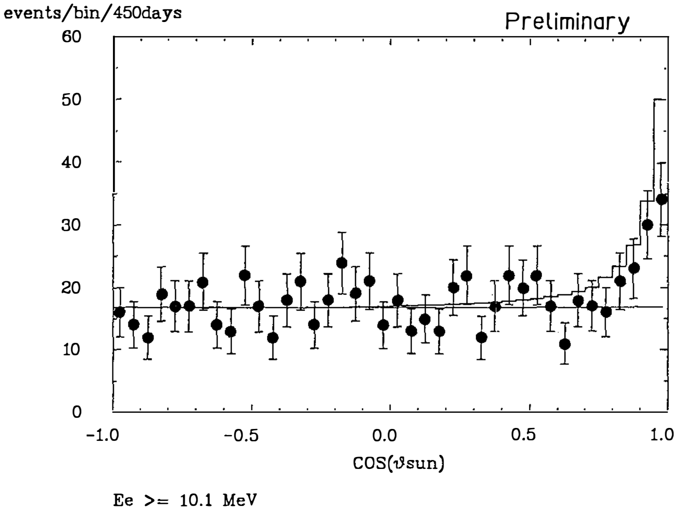

Figure 2. Distribution in $\cos\theta_{sun}$, the cosine of the angle between the trajectory of an electron and the direction of the sun at a given time. The curves plotted are in the 680 ton fiducial mass, have $E_e \geq 10.1$ MeV, and events identified as from spallation products or remaining gamma-rays have been excluded.

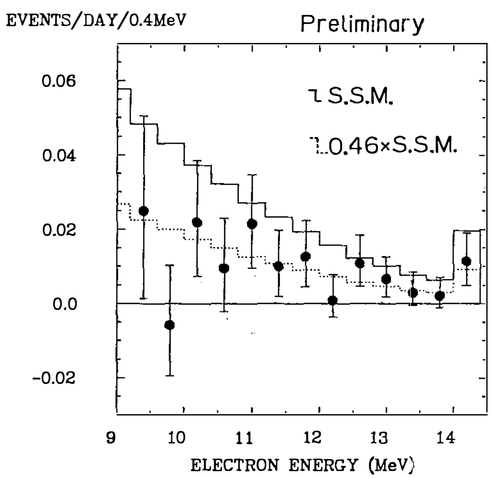

Figure 3. Energy distribution of the events in the fiducial mass after background subtraction (see text). The histogram is the distribution predicted by the standard solar model.

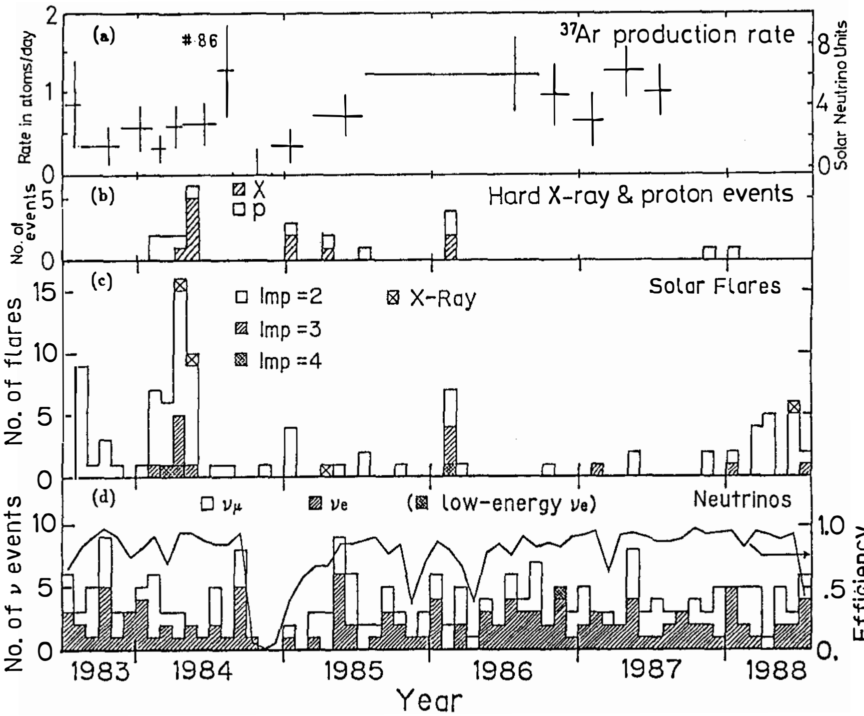

Figure 4. (a) ^{37}Ar production rate in the ^{37}Cl experiment.[8]. (b) Number of solar hard X-ray and proton events. (c) Number of solar flares with optical *importance* ≥ 2 or maximum X-ray importance X with optical *importance* ≤ 1. (d) Number of single-ring ν_e and ν_μ events observed by the KAMIOKANDE detector. The monthly data-taking efficiency is also shown by the solid line (right vertical scale).

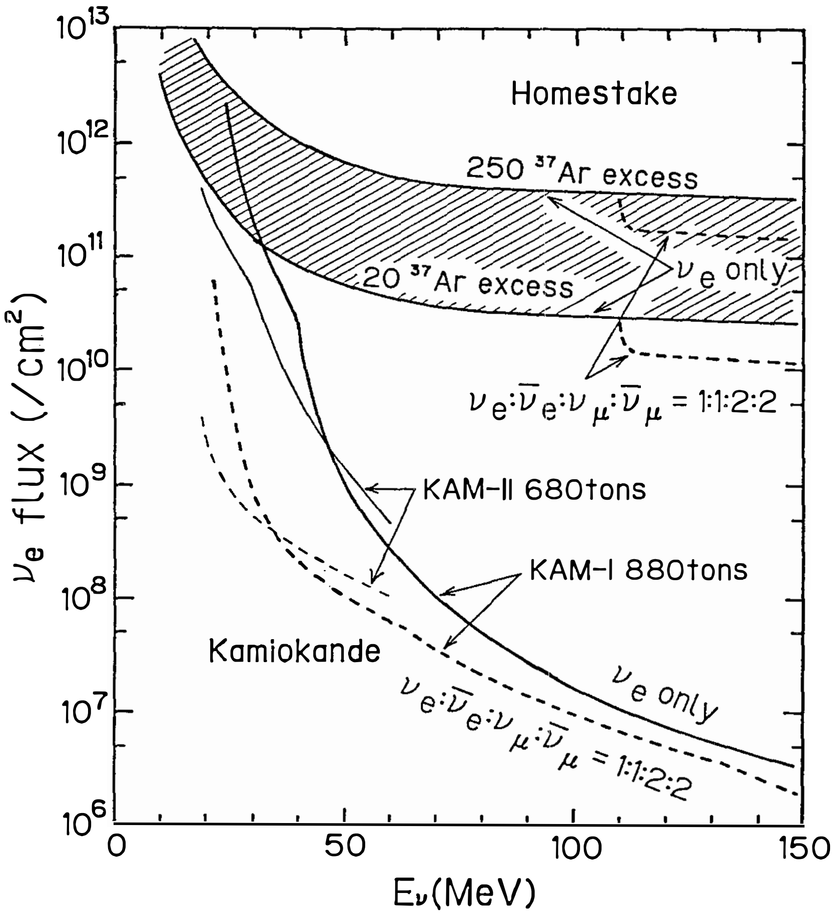

Figure 5. The sensitivity of the KAMIOKANDE detector to the solar-flare ν_e flux is plotted as a function of ν_e energy, corresponding to one neutrino event in the detector. The shaded region indicates the solar-flare ν_e flux estimated from the results of the ^{37}Cl experiment.