BIRTH OF NEUTRINO ASTROPHYSICS

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by

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In giving this talk I am very much helped by the preceding talk because I can skip some of the topics. If you want further information, please refer to my review article, "Observational Neutrino Astrophysics," [1].

I am to talk about the birth of the neutrino astrophysics, but before the birth, there was a very important event, which was just described by Prof. Davis. [2]. It was the radiochemical work using the reaction $\nu_e + {}^{37}\mathrm{Cl}$ going to $e + {}^{37}\mathrm{Ar}$. He found that the observed neutrino flux was only 1/3 of the theoretically expected. This could be considered as the conception of the neutrino astrophysics and was in fact the impetus for us to begin seriously working on the solar neutrinos.

I will talk about two experiments. The first is the original KamiokaNDE, which might be called an Imaging Water Cerenkov detector with a surface coverage of 20% by photomultipliers and the total mass of the water inside this detector is 3,000 tons. It costed about 3 million U.S. dollars. This, mind you, was meant to be the feasibility experiment on the astrophysical detection of solar neutrinos. The second experiment is called Super-KamiokaNDE, the same type of detector but with a better light sensitivity, that is, 40% of the entire surface was covered by the photocathode and the total mass of the water was 50,000 tons. It costed about 100 million U.S. dollars. This was considered to be the full-scale solar neutrino observatory.

Both the experiments are situated about 1,000 meters underground in Kamioka Mine. The capital letters NDE at the end of the two experiments originally implied "Nucleon Decay Experiment." However, because of our detection of various neutrinos by these detectors, people started calling it, "Neutrino Detection Experiment".

Fig.1 shows the interior of KamiokaNDE. You can see arrays of photomultipliers on the sidewalls as well as on the top and at the bottom. When we were preparing for this KamiokaNDE experiment, we heard that a much bigger, experiment but of similar type, was being planned in the United States. [3]. We had to think very seriously about the competition with this bigger detector. Both experiments aimed at the detection of a certain type of proton decay, i.e., $e^+ + \pi^0$ mode. If we were aiming only for the detection of such particular types of proton decays, certainly the much bigger U.S. experiments would

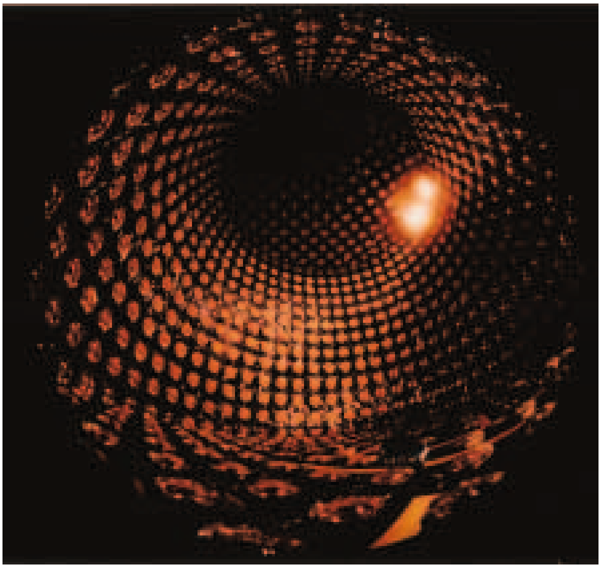


Figure 1. The interior of KamiokaNDE.

Figure 2. The newly developed large photomultiplier.

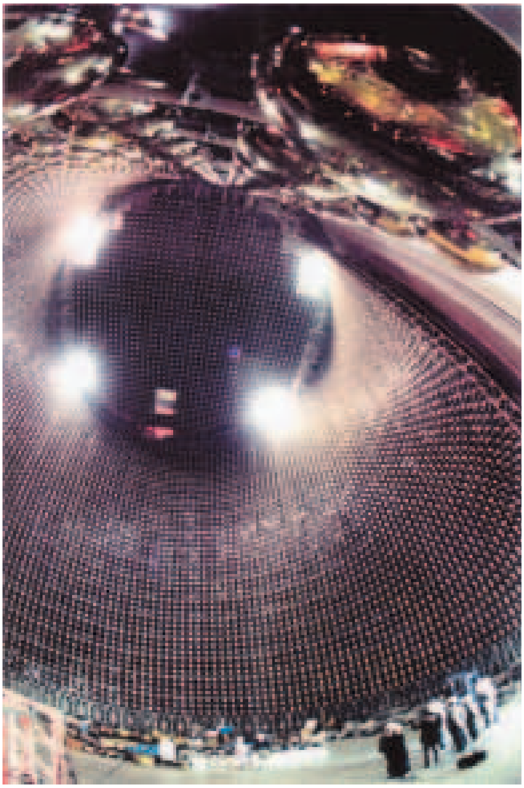


Figure 3. The interior of S-K through fish-eye lens.

find it first. Then, what could we do with a smaller detector? We thought very seriously about this competition and we came to the conclusion that the only possible way to compete with this bigger detector would be to make our detector much more sensitive than the U.S. competitors so that we could not only detect the easiest proton decay mode, but also measure other types of proton decays. Then eventually we could say that the proton decays into this mode with this branching ratio and into that mode with that branching ratio and so forth. Then our experiment would be able to point the way to the possible future, what is called the Grand Unified Theory, which is a new type of theory combining strong forces, weak forces, and electromagnetic forces.

Thanks to the cooperation of Hamamatsu Photonics Co., we jointly developed very large photomultiplier tubes [4]. I was so happy, as you can see in Fig. 2 that this tube was successfully developed.

Fig. 3 shows the fish-eye view of the Super-KamiokaNDE interior. You can see many more phototubes, a total of about 11,000 big phototubes.

Since I suppose that not many people are familiar with this type of detector, I want to show you the performance of Super-KamiokaNDE. The first example is a very slow motion picture of a cosmic ray muon passing through the detector.

Figure 4-1. μ just entered S-K.

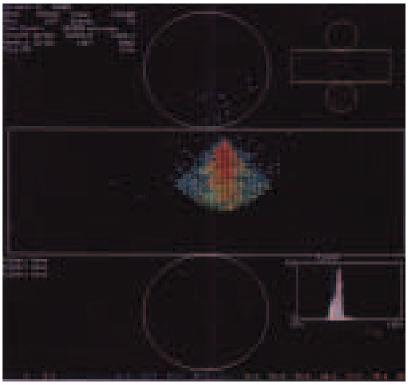


Figure 4-2. 50 nanoseconds later.

As is well known, special relativity prohibits any particle to move faster than the velocity of light in vacuum. However, in a media like water, the light velocity itself is reduced to three-quarter of its value in vacuum. Therefore, when the particle energy is very high, its velocity can exceed the velocity of light in the water. Then, what happens is that such high energy, high velocity, particles in water will generate, what might be called, a shock wave of light; the Cerenkov light. It is emitted in a cone shape with the axis on the trajectory of the moving electrically charged particle.

Fig. 4-1 shows the response of Super-KamiokaNDE when a muon just entered the detector. The Super-KamiokaNDE detector is opened up here. The sidewall is cut vertically at one point and is spread flat, the upper lid is opened up, and the bottom lid is pulled down. Each dot here represents a photomultiplier. Red light shows it received a large number of photoelectrons. The different colors indicate different numbers of received photoelectrons. At the right below is the time profile of the total number of photons received. Fig. 4-2 shows the pattern 50 nanoseconds later. You can see that the particle is moving faster than the Cerenkov light wave front. Fig. 4-3 , another 50 nanoseconds later, shows that while the Cerenkov light is still on its way the muon has already reached the bottom. You can see that the particle is traveling faster than the light velocity in water. Figs. 4-4, 4-5, and 4-6 show the subsequent development of the event. You can see that with this detector the electrically charged particle can be observed in detail. Next figure, Fig. 5, shows two events, e-event above and μ-event below. Looking at these two examples, one by an electron and the other by a muon, you can see the difference in the distribution of the detected photons, especially in the radial distribution of photons. Electrons and muons are very similar particles except that their masses are different by a factor of about 200. It means that in traversing water, the heavier μ-particle suffers much less scattering while the lighter electron gets scattered much more. Not only that, the electron emits γ-rays, which in turn get converted into electrons and positrons. Those low energy electrons, and positrons, get scattered violently. Therefore, the

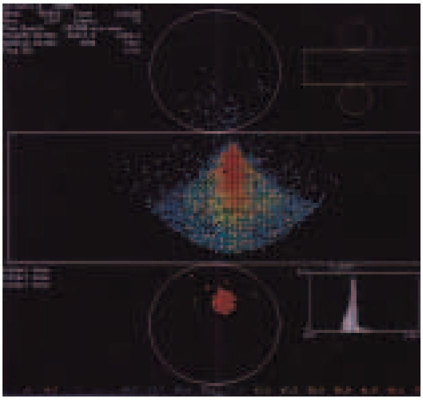


Figure 4-3. μ reached the bottom.

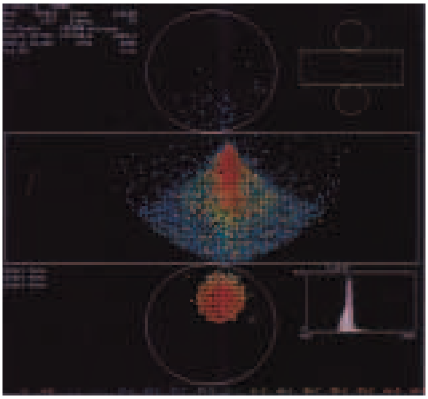


Figure 4-4.

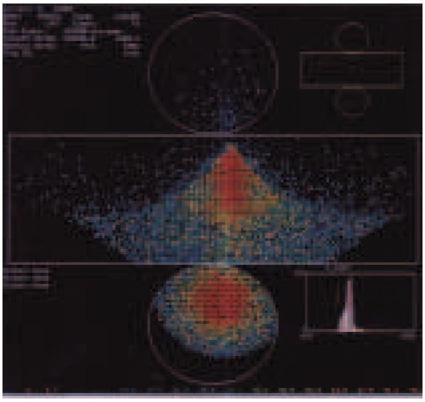


Figure 4-5.

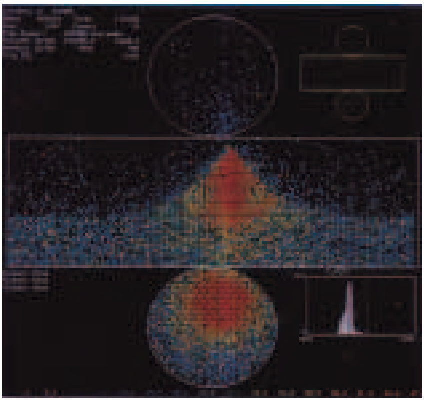


Figure 4-6.

Cerenkov light emitted by those low energy particles is widely distributed as you see in the upper event. By making a quantitative measurement of the radial distribution of those photons, you can make a very good distinction between a μ-event and an e-event with a mistaking probability of less than 1%. This is a very nice feature of this detector and led us eventually to discover what is called "the atmospheric neutrino anomaly."

The old KamiokaNDE produced four significant results.

The first is the astrophysical observation of solar neutrinos by means of ν_e-e scattering with the electron in the water. [5]. By astrophysical observation we mean that all the necessary information is available; i.e., the arrival direction, the arrival time and also the spectral information on the incoming neutrinos. In the case of ν_e-e scattering, since the electron rest mass is only 0.5 MeV, for an incoming neutrino of, say, 10 MeV, the struck electron goes almost in the dead forward direction. By observing this recoil electron, you can approximately infer the arrival direction of the neutrino. Also, the energy spectrum of the recoil electrons has a one to one relation to the original neu-

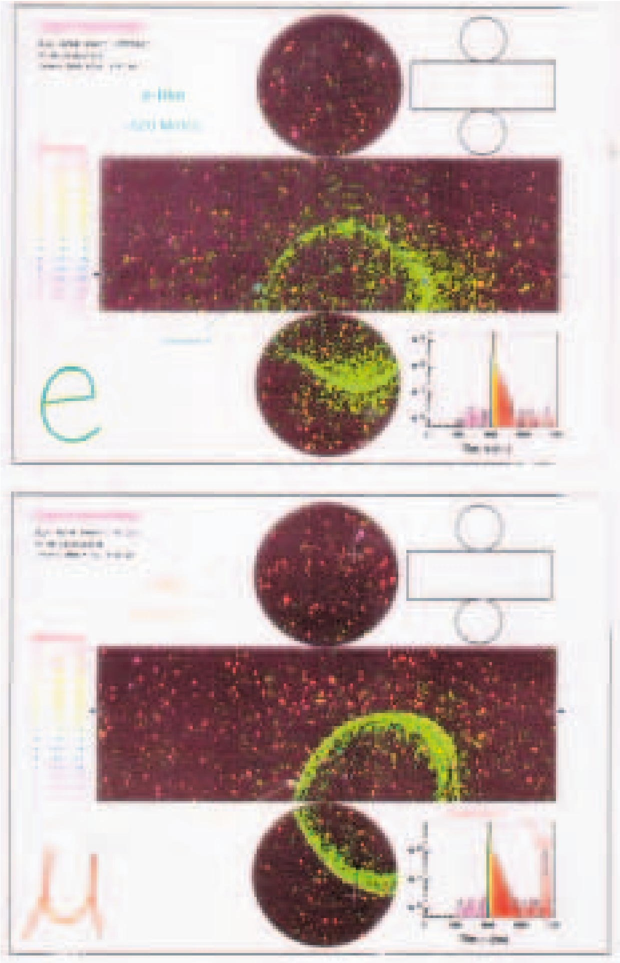


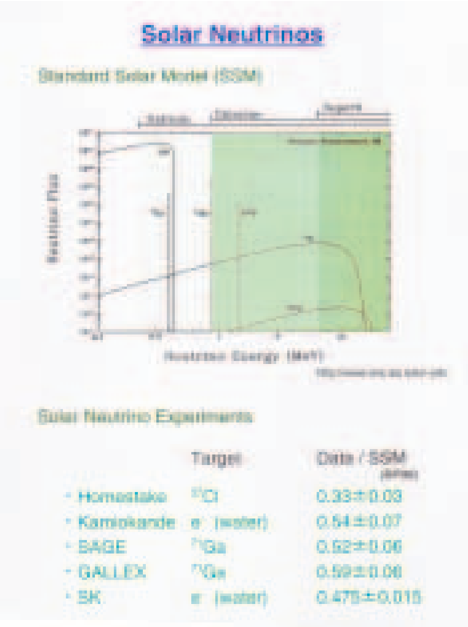
Figure 5. e-event above and μ-event below.

trino energy spectrum. The timing is accurate to better than ten nanoseconds.

The second is the observation of supernova neutrinos [6] by means of anti-ν_e on protons in water. This reaction produces an e^+ and a neutron. The e^+ is observed by the Cerenkov light it emits.

The third is the discovery of what is called the Atmospheric Neutrino Anomaly. [7]. Since we can definitely separate μ-event and e-event, as I have shown you before, we could measure the number ratio of ν_μ over ν_e very accurately by observing μ-event and e-event separately. It was the discovery of slightly more than 4 significance, but this result was later firmly confirmed at more than 9σ by the data of Super-KamiokaNDE.

Not many people are interested in proton decay any more but the non-observation of proton decay by the KamiokaNDE experiment killed the well-known Grand Unified Theory based on SU[5].



Solar Neutrinos

Standard Solar Model (SSM)

Solar Neutrino Experiments

	Target	Data / SSM
Homestake	^{37}Cl	0.33±0.03
Kamiokande	e^- (water)	0.54±0.07
SAGE	^{71}Ga	0.52±0.06
GALLEX	^{71}Ga	0.59±0.06
SK	e^- (water)	0.475±0.015

Figure 6.

The previous speaker showed this diagram, Fig. 6, and I am not going into the detail here but instead just ask you to notice the threshold energies of various experiments.

Fig. 7 is to shows the feasibility for KamiokaNDE of observing solar neutrinos with directional information. You can see that above the isotropic background, the accumulation of events is in the direction from the sun to the earth.

Next one, Fig. 8, shows the energy spectrum as normalized to the theoretical one. From the figure you can see that the shape is not very much differ-

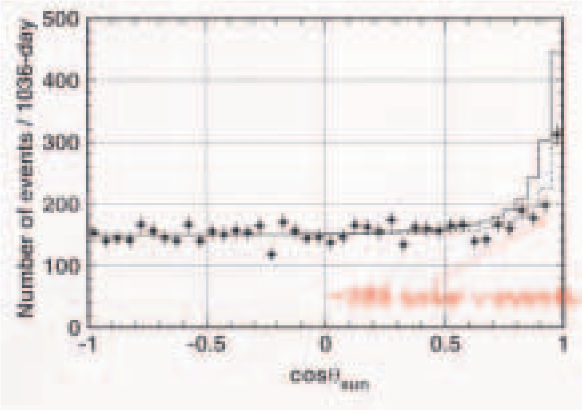


Figure 7. The directional observation of Solar neutrinos.

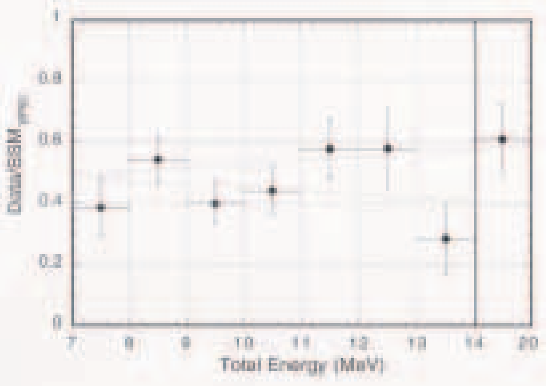


Figure 8. The normalized energy spectrum.

ent from the expected theoretical anticipation, but the intensity is almost one-half.

I now go on to the observation of supernova neutrinos. Thanks to the collaboration of Pennsylvania State University led by Prof. A. K. Mann, we could improve the performance of our detector very much by reducing the background, purifying the water, and so forth. At the very beginning of 1987; our detector was already calm enough to start taking data on the solar neutrinos. Two months later, we heard that there was a supernova explosion in the southern sky. So we immediately looked at our data and then we found the supernova neutrino signal very easily because our detector was already capable of taking solar neutrino data, which are much more difficult to observe than the supernova neutrinos; because the supernova neutrinos have considerably higher energies than the solar neutrino and furthermore those supernova neutrinos are bunched in a short period of time. It is shown in Fig. 9. You can clearly see the supernova neutrino signal of about 17 photoelectrons above the background events. This observation gave the confirmation of theoretical ideas on the supernova explosion triggered by a gravitational collapse. For instance, not only the average energy and the total number of these events agreed with the theoretical expectations, but also the time duration of about ten seconds implies that those neutrinos are emitted from a very, very dense matter, like in a nucleus.

If they were emitted from a tenuous stellar body, the time duration of the signal would have been less than one millisecond. But those neutrinos had to get diffused out of a very dense, nucleus-like, matter so that it took ten seconds to get out of this surface; probably a neutron star is responsible.

Now I come to the discussion of "the Atmospheric Neutrino Anomaly." When cosmic ray particles enter the atmosphere, they interact with the N and O nuclei to produce π-mesons and K-mesons. These mesons decay in tenuous air into μ and ν_μ. So you get one muon and one ν_μ there. If the secondary μ also decayed then you get additional ν_μ and ν_e. So if everything proceeded this way, you get two ν_μ's against one ν_e. The number ratio, N (ν_μ) / N (ν_e) is

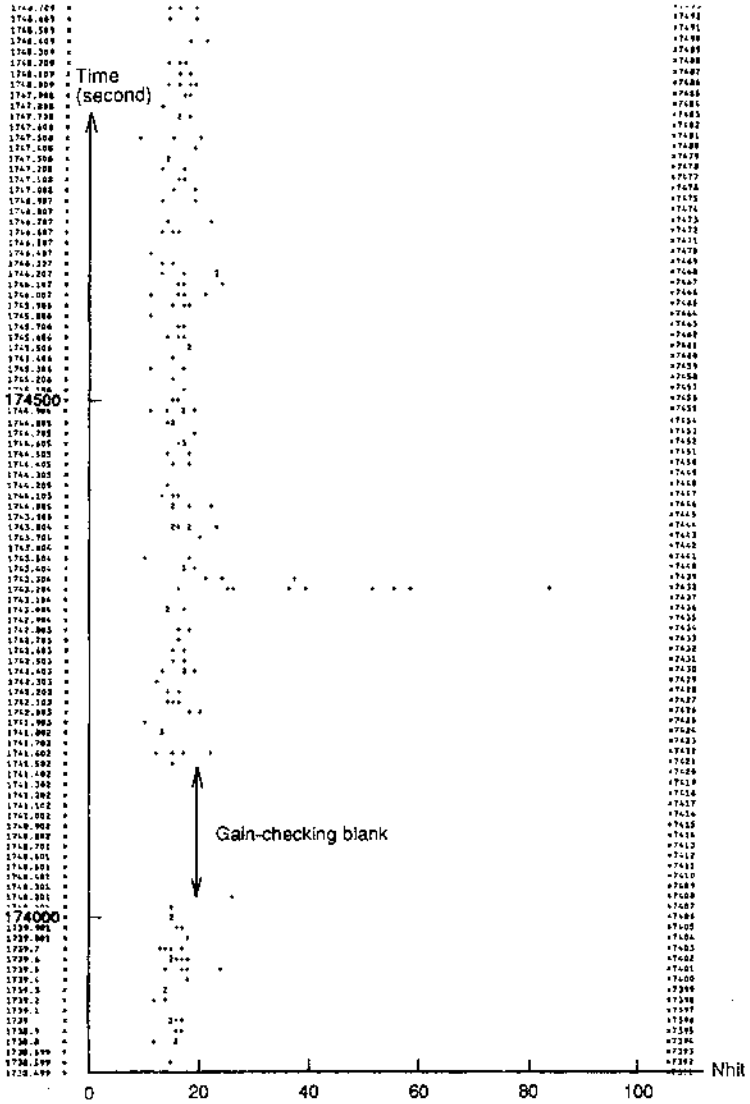


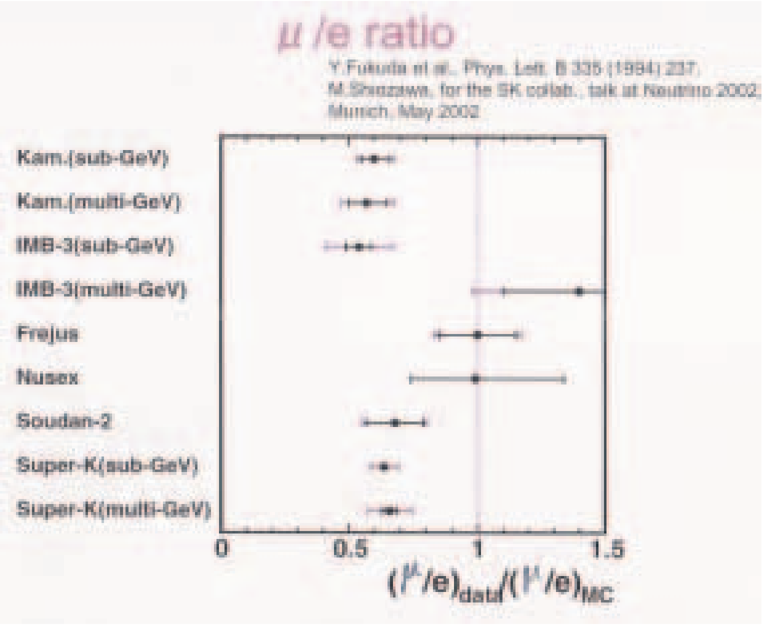
Figure 9. The SN1987A neutrine "signal" in the computer print-out.

thus two. When you go to higher energy, a μ of longer lifetime than a π-meson cannot decay. Indeed, some μ's do reach our detector, as you have seen before. In this case, you do not get additional ν_μ or ν_e. So at high energies, this ratio becomes larger than two.

In Fig. 10 are shown the above number ratio observed by KamiokaNDE together with the results of other experiments.

I now go on to the discussion of the neutrino oscillations, [9]. This may be the most difficult part of my talk. I will try to make it understandable to a first year undergraduate student.

For the sake of simplicity, we consider there are only two kinds of neutrinos



μ /e ratio

Y.Fukuda et al., Phys. Lett. B 335 (1994) 237.
M.Shiozawa, for the SK collab., talk at Neutrino 2002,
Munich, May 2002

Figure 10. The number ratio N ($\nu\mu$) / N (ν_e).

in nature. Then, for instance, the wave function describing the state of a neutrino can be described by a linear combination of two independent base functions. For instance, you can take the mass matrix to be diagonal and then choose the two basic vectors of mass m_1 and mass m_2, respectively. So any neutrino state can be described by a combination of ϕ_{m1} and ϕ_{m2}. $\phi_{\nu\mu} = \cos\phi\ \phi_{m1} + \sin\phi\ \phi_{m2}$. This is like two-dimensional geometry. A vector can be described by its x component and y component. So the ν_μ state is a linear combination of m_1 state and m_2 state with an angle parameter θ. The two states, ϕ_{m1} and ϕ_{m2}, oscillate with their characteristic frequencies. This frequency is proportional to the total energy of the state. If the mass m is small, then for a given momentum one can make the following approximation, $E \sim p + m^2/2p$. $E_1 - E_2$, which is proportional to the frequency difference of these two states, is then, using this approximation, proportional to $(m_1^2 - m_2^2)$. This m-square difference between the two states is designated by Δm^2. When there are two oscillations of nearly equal frequencies coexist, there occurs a phenomenon known as "beat" in which the amplitudes of the two oscillations change slowly with the difference frequency. This change of the component amplitudes, ϕ_{m1} and ϕ_{m2}, induces the appearance of ν_τ-state in the original pure ν_μ state.

By using these two parameters, Δm^2 and ϕ, you can describe the oscillation of neutrinos from one type to the other.

In Fig. 11 is shown the result obtained by KamiokaNDE, [10] , on the atmospheric neutrino oscillations.

We now proceed to the discussion of Super-KamiokaNDE.

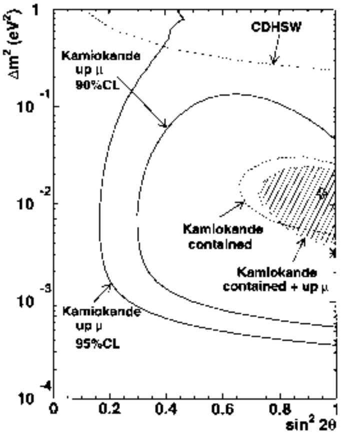


Figure 11. The allowed parameter region.

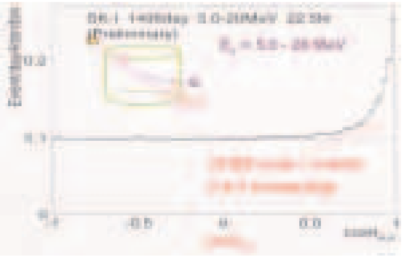


Figure 12. The directional observation.

The Super-KamiokaNDE so far produced three significant results.

The first is the astrophysical observation of the solar neutrinos with a comfortable statistics. In Fig. 12 you can see the peak of neutrinos in the direction from the sun to the earth above the isotropic background. When you break your hand you go to the doctor and get an X-ray picture taken. You then can see the inside of your hand. A bone may be broken. When you use neutrinos, with a much larger penetrability, you can see the inside of the sun. In Fig. 13

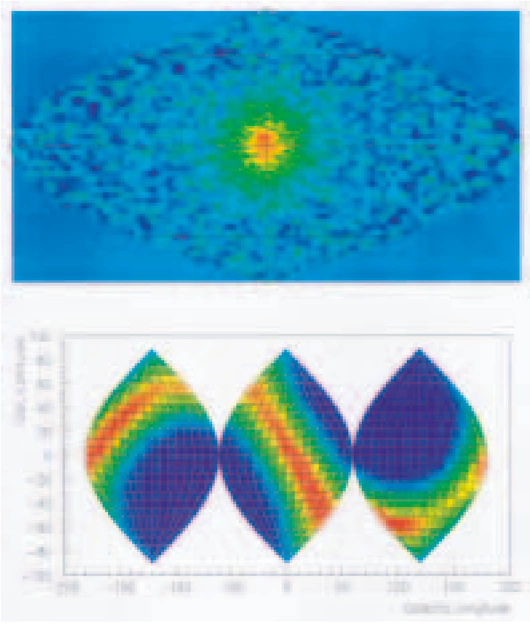


Figure 13. The neutrinograph of the sun.

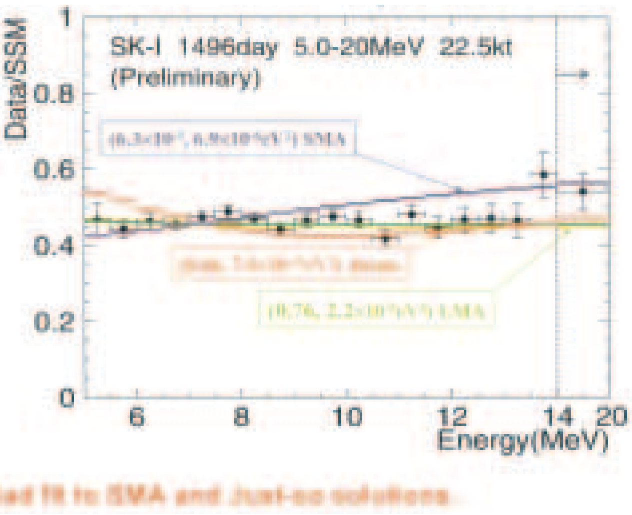


Figure 14. The energy spectrum.

is shown the first neutrinograph, rather than photograph, of the sun. Below is the orbit of the sun in the galactic coordinates as seen by the neutrinos.

This sounds very nice, but if you look at this neutrinograph carefully, you find the size of sun is much bigger than the size of sun as you see by your own eyes. The reason is, of course, that the directional accuracy of the neutrino observation is much worse than that of visible light. But you have to be patient. The neutrino astrophysics is just born. It is still in its infantile stage.

Fig. 14 shows the observation of the solar neutrino energy spectrum as compared to the theoretically expected from the Solar Standard Model.

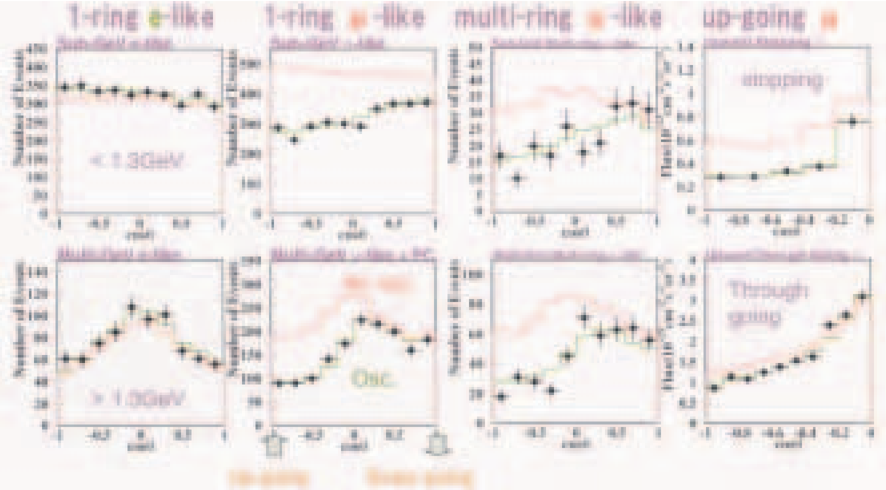


Figure 15. The change of oscillation as a function of path length.

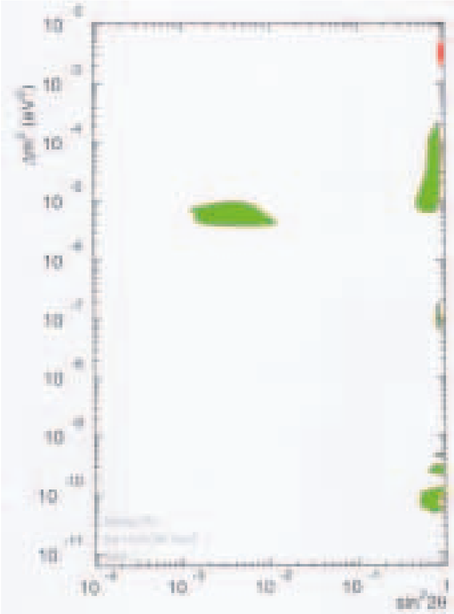


Figure 16. The allowed regions of oscillations.

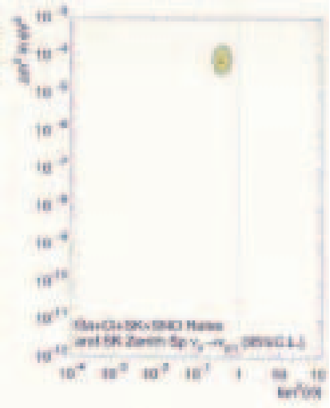


Figure 17. The allowed region for the solar neutrino oscillation.

Detailed comparison of this observed energy spectrum with the theoretical expectation gives us better information on the solar neutrino oscillation.

If the observed anomaly in the N (ν_μ) / N (ν_e) is indeed due to the neutrino oscillation, then the degree of oscillation would be different depending on the path lengths the neutrino had to traverse from its generation to our detector. When it comes from vertically above, it is only 20 kilometers. When it comes horizontally, it traveled some 1,000 kilometers. If it comes from the bottom, it was produced 13,000 kilometers away. There is a big difference in the path lengths (Fig. 15).

In the case of e-events, due to ν_e , there is no deviation from the no-oscillation expectation. Only in the case of μ-events, due to ν_μ, one sees a large reduction in the direction from the bottom. Only in the case of muon, you see this deficiency in the large distance direction. Fig. 16 shows the allowed regions for the solar neutrino oscillations, painted yellow, and that of atmospheric neutrino oscillations, painted red as determined by the data of Super-KamiokaNDE ,[11].

With the oscillation data described above of KamiokaNDE and of Super-KamiokaNDE we go on to combine them with the other available data. Next figure, Fig. 17, shows only one possible oscillation region for the solar neutrino oscillation. This was accomplished by combining all the solar neutrino experiments. Super-KamiokaNDE, SNO and other radio-chemical results [14–17].

Now that the observed Δm^2 's are definitely not zero we have to admit

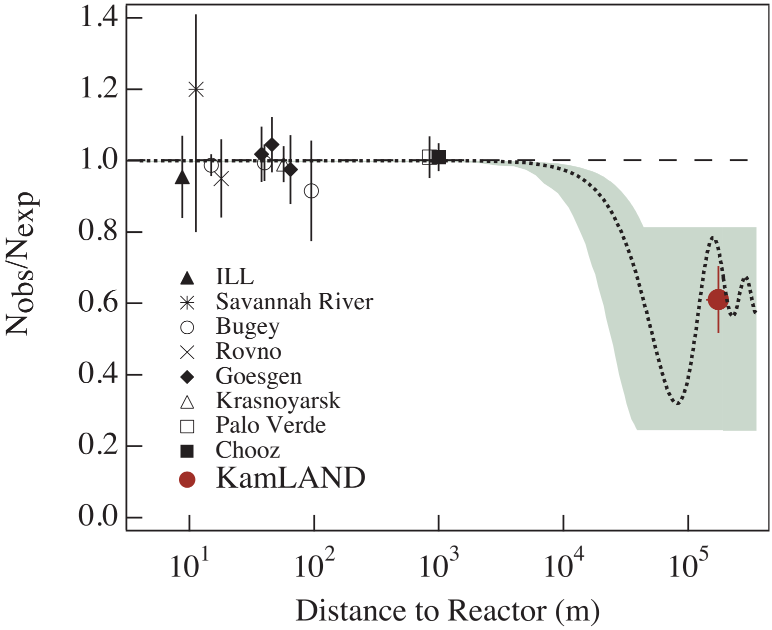


Figure 18. Results from KamLAND.

some non-zero masses for the neutrinos. This implies that the Standard Theory of elementary particles have to be modified.

Now, for the sake of giving proper credits, I give the author list of supernova neutrino detection in ref. [6] and the author list of the atmospheric neutrino paper in [12].

Lastly I show you the latest result from Kamioka. In Kamioka, there is a third generation experiment now working. This KamLAND experiment is installed in the old cave of the original KamiokaNDE and this experiment uses liquid scintillator to measure the anti-ν_e's from the reactors about 200 kilometers away. And this experiment published their first result [18] only two days ago and I got this by e-mail. The experiment is measuring the anti-neutrino flux as well as the energy spectrum. The result is shown in Fig. 18. The obtained oscillation parameters, $\sin 2\phi = 0.833$ and $\Delta m^2 = 5.5\text{x}10^{-5}$ $(\text{eV})^2$, are in good agreement with the solar neutrino result of Fig.18.

Since this is a confirmation of the neutrino oscillation not for the electron neutrino but for anti-electron-neutrino, the fact that it is giving the same oscillation parameters implies that the CPT theorem is not violated. Further data accumulation may lead to some interesting insight into the CP problem within the framework of CPT invariance. Reference to this paper is given in [18]. The interesting thing is that about two-thirds of the collaborators are from the United States. Some say Kamioka is now considered as the "Mecca" for neutrino research and this pleases me very much.

Now that Neutrino Astrophysics is born, what should we do next? Of course the plan depends on whom we ask. There is a move to build a megaton Hyper-KamiokaNDE. A world network of at least three Super-KamiokaNDE's may be a good choice for supernova watching. The most challenging problem will be the observation of the Cosmic Neutrino Background of 1.9K, which would tell us the state of our universe 1 second after its birth. The non-zero masses of neutrinos imply the total reflection at low temperature of low energy neutrinos. This is a wonderful gift providing the possibility of parabolic mirror for focusing CNB. The detection, however, of such low energy neutrinos is really a formidable task.

ACKNOWLEDGEMENTS

It is my pleasure to acknowledge the technical contribution of Hamamatsu Photonics Co. for producing the 50cmϕ photomultipliers. They were the essential ingredient of the Kamioka experiments. The Ministry of Education, Culture and Science of Japan gave generous support to the Kamioka experiments, for which we are all grateful.

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