CHEMPHYSCHEM

Birth of Neutrino Astrophysics (Nobel Lecture)**

Masatoshi Koshiba*[a]

The KamiokaNDE experiment for the observation of proton decay, an array of photomultipliers containing over 3 000 tons of water, allowed the observation of charged particles travelling faster than the velocity of light in water. The subsequently developed Super-KamiokaNDE could be used to measure the amounts, the path, the energies, and the oscillation parameters of neutrinos, generated either by supernova explosions in the sun, or in the atmosphere. This work was awarded the 2002 Nobel Prize in Physics.

KEYWORDS:

astrophysics · neutrinos · Nobel lecture · proton decay

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 neutrino astrophysics, but before the birth, there was a very important event, which was just described by Prof. Davis.[2] This was the radiochemical work using the reaction [Eq. (1)]:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar} \quad (1)$$

He found that the observed neutrino flux was only 1/3 of that theoretically expected. This could be considered as the conception of neutrino astrophysics and was in fact the impetus for us to begin seriously working on 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 20% surface coverage by photomultipliers; it cost about three million U.S. dollars. This was meant to be the feasibility experiment on the astrophysical detection of solar neutrinos. The second experiment is called Super-KamiokaNDE, and uses 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 cost 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".

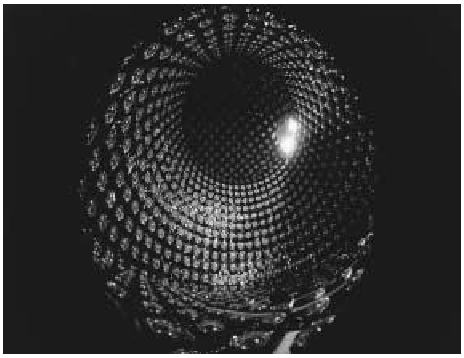

Figure 1. The interior of KamiokaNDE.

Figure 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 a 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, that is, $e^+ + \pi^0$ mode. If we were aiming only for the detection of such particular type of proton decays, certainly much bigger U.S. experiments would have found 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 was to make our detector much more sensitive than the U.S. competitors, so that we can not only detect the easiest proton decay mode, but we can also measure other types of proton decays. Then, eventually, we should be able to say that a proton decays into this mode with this branching ratio and into that mode with that branching ratio, and so forth, so that our experiment should be able to point the way to the possible future theory; this future theory is called 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 this very large photomultiplier tube.[4] I was so happy, as you can see in Figure 2, that this tube was successfully

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Figure 2. The newly developed large photomultiplier.

developed. Figure 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 not many people are familiar with this type of detector, I want to show you the performance of Super-KamiokaNDE. The first example (see Figure 4) is a very slow motion picture of a cosmic ray muon passing through the detector.

As is well known, special relativity prohibits any particle from moving faster than the velocity of light in a vacuum. However, in a media such as water, the light velocity itself is reduced to three-quarters 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 a high energy, high velocity particle in water will generate what might be called a "shock wave of light"; the Cerenkov light. This light is emitted in a cone shape with the axis on the trajectory of the moving electrically charged particle.

Figure 4a shows the response of Super-KamiokaNDE when a muon just entered the detector. The Super-KamiokaNDE detector is expanded 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 that the photomultiplier received a large number of photoelectrons. The different colors indicate a different number of received photoelectrons. At the right, below, is the time profile of the total number of photons received. Figure 4b shows the pattern 50 ns later. Figure 4c, another 50 ns later, shows that while the Cerenkov light is still on its way, the muon has already reached the bottom of the tank. You can see that the particle is traveling faster than the light velocity in water. Figures 4d, 4e, and 4f show the subsequent development of the event. You can see that, with this detector, the electrically charged particle can be observed in detail. The next figure, Figure 5, shows two events, the e event and the μ event. Looking at these two examples, one by the electron and the other by the muon (μ), 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 emits γ rays, which in turn are converted into electrons and positrons. These low energy electrons and positrons are scattered violently. Therefore, the Cerenkov light emitted by these low energy particles is widely distributed, as you see in the upper event. By making a quantitative measurement of the radial distribution of the photons, you can make a very good distinction between a μ event and an e event, with an error 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 result is the astrophysical observation of solar neutrinos by means of $\nu_e - e$ scattering with the electron in the water.[5] By "astrophysical observation" we mean that all the necessary information is available; that is, the arrival direction, the arrival time and also the spectral information on the incoming

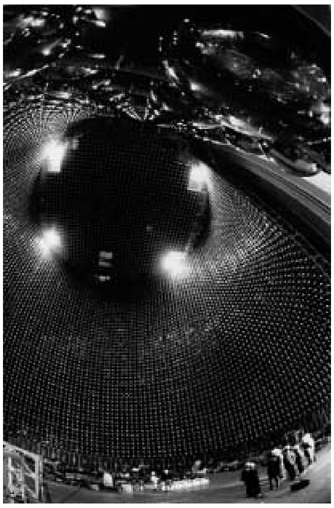


Figure 3. The interior of Super-KamiokaNDE through a fish-eye lens.

Professor Koshiba was born on September 19, 1926 in Toyohashi city, Aichi Prefecture, Japan. He graduated from the University of Tokyo in 1951. In 1955 he completed Graduate School at the University of Rochester, Rochester, N.Y. and received his Ph.D. in physics. In 1970, he became Professor of the Department of Physics, Faculty of Science, University of Tokyo. In 1987 he retired from University of Tokyo, and became Emeritus Professor. He was Professor of Tokai University from 1987 to 1997. He has played leading roles in experiments on cosmic ray physics, notably KamiokaNDE and Super-KamiokaNDE, as well as experiments in high energy physics using the electron–positron colliders with the highest energies. He has been awarded numerous honors and prizes including; der Grosse Verdienstkreutz from the President of Federal Republic of Germany (1985), the Nishina Prize from the Nishina Foundation (1987), the Asahi Prize from the Asahi Press (1988, 1999), the Order of Culture by the Japanese Government (1988), the Academy Award from the Academy of Japan (1989), the Fujiwara Prize from the Fujiwara Science Foundation (1997), the Order of Cultural Merit conferred by the Emperor of Japan in person (1997), the Wolf Prize from the State President of Israel (2000), and the Nobel Prize for Physics (2002).

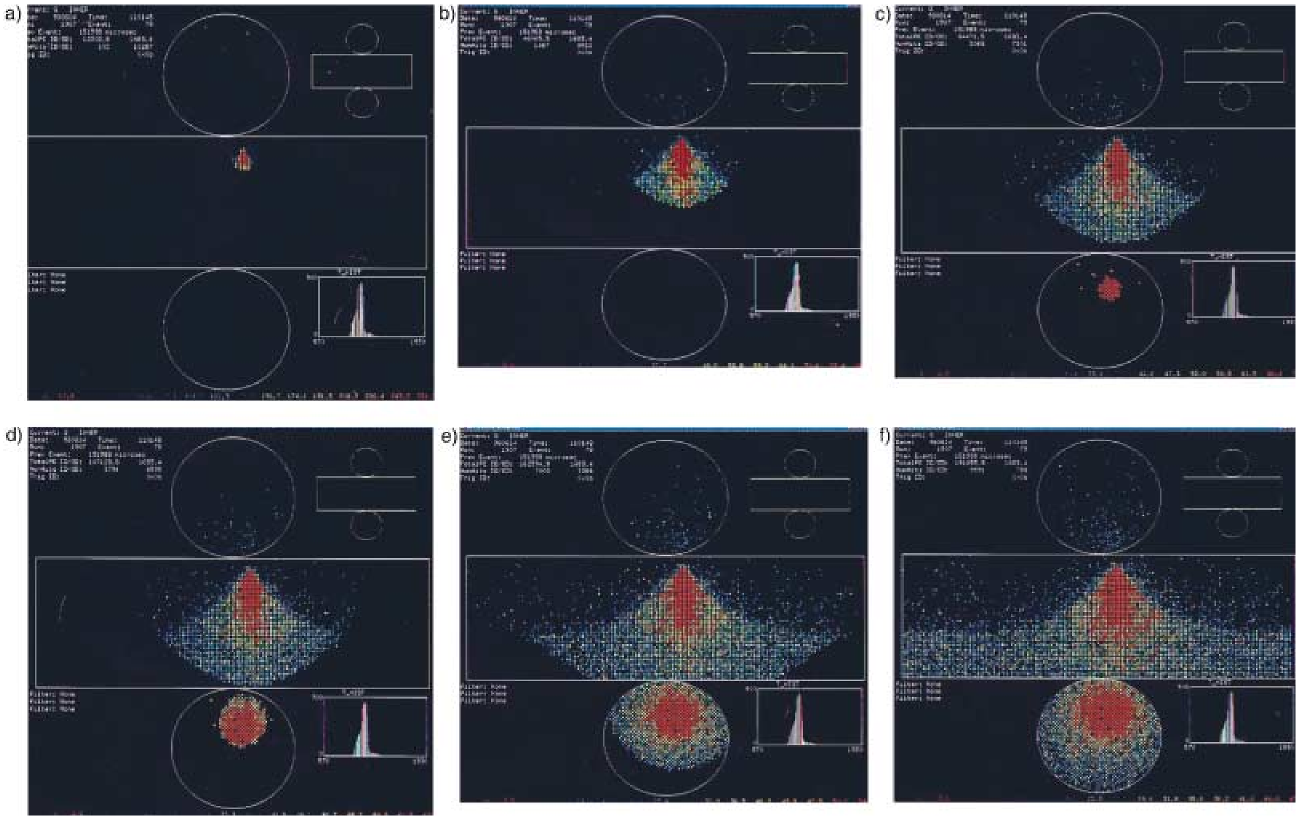


Figure 4. *a) Super-KamiokaNDE response after a muon has just entered the detector; b) 50 ns later; c) the muon has reached the bottom of the detector; d – f) further development.*

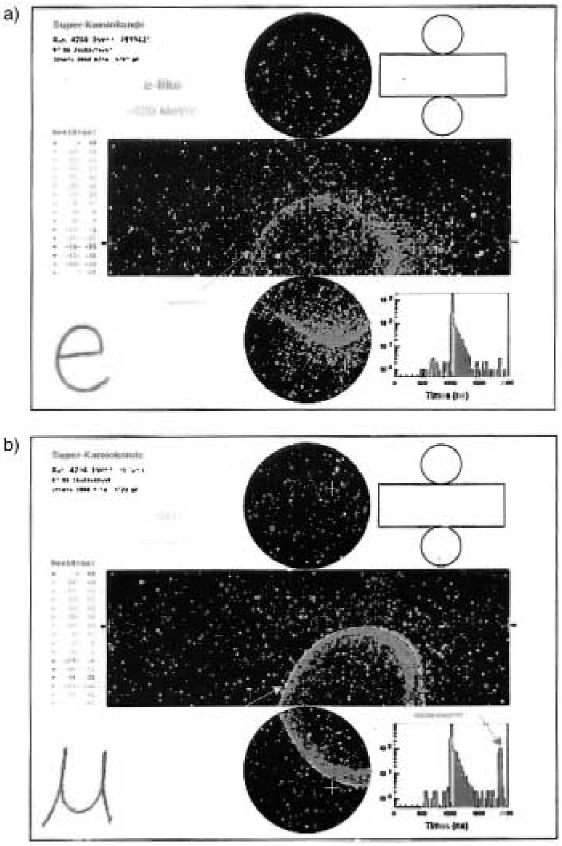


Figure 5. a) e event and *b) m event.*

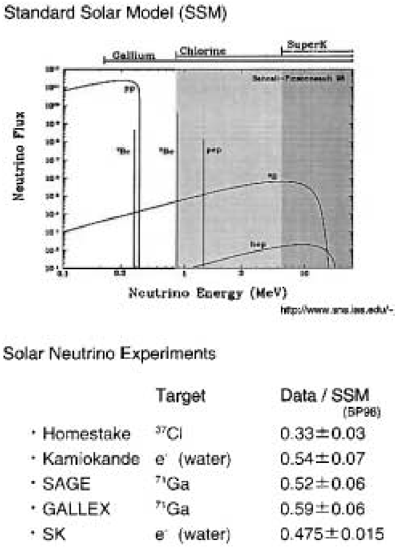
neutrinos. In the case of ν_e – e scattering, since the electron rest mass is only 0.5 MeV, for an incoming neutrino of, say, 10 MeV neutrino, the struck electron goes almost in the straightforward direction. By observing this recoil electron, you can approximately infer the arrival direction of the neutrino. Also, the energy spectrum of the recoil electrons has a one to one relation to the original neutrino energy spectrum. The timing is accurate to better than 10 ns.

The second result is the observation of supernova neutrinos[6] by means of the reaction 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 result is the discovery of what is called “atmospheric neutrino anomaly”.[7] Since we can definitely distinguish the ν event from the e event, as I have shown you before, we could measure the number ratio of ν_μ over ν_e very accurately by observing the μ event and the e event separately. The ratio was first observed to be half of the expected at slightly more than four σ significance, but this result was later firmly confirmed at more than nine σ by the data of the Super-KamiokaNDE.

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

Figure 6 shows the theoretical expectation of the polar neutrino energy spectrum. I am not going into the detail here but instead just ask you to notice the threshold energies of various experiments.



	Target	Data / SSM (BP98)
• 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. *Standard solar model, showing threshold values.*

Figure 7 is to show the feasibility data from KamiokaNDE of observing solar neutrinos with its directional information. You can see above the isotropic background, the accumulation of event in the direction from the sun to the earth.

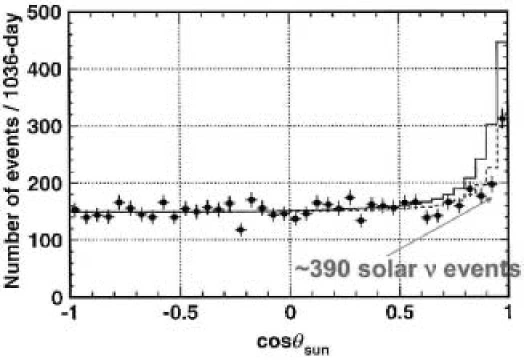


Figure 7. *The directional observation of Solar neutrinos.*

The next one, Figure 8, shows the energy spectrum as normalized to the theoretical one. From the figure you can see the shape is not very much different to the expected theoretical expectation, but the intensity is almost one half of this.

I now go on to discuss 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 greatly 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 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. This is because the supernova neutrinos have considerably higher energies than the solar neutrino and furthermore the supernova neutrinos are bunched in a short period of time. These data are shown in Figure 9. You can clearly see the supernova neutrino signal above the background events of about 17 photoelectrons. This observation did give the confirmation of theoretical ideas on the supernova explosion triggered by a gravitational collapse.

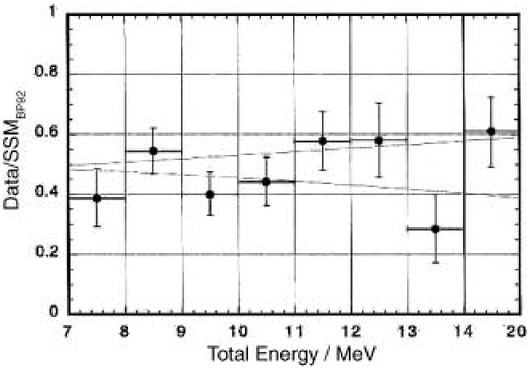


Figure 8. *The normalized energy spectrum.*

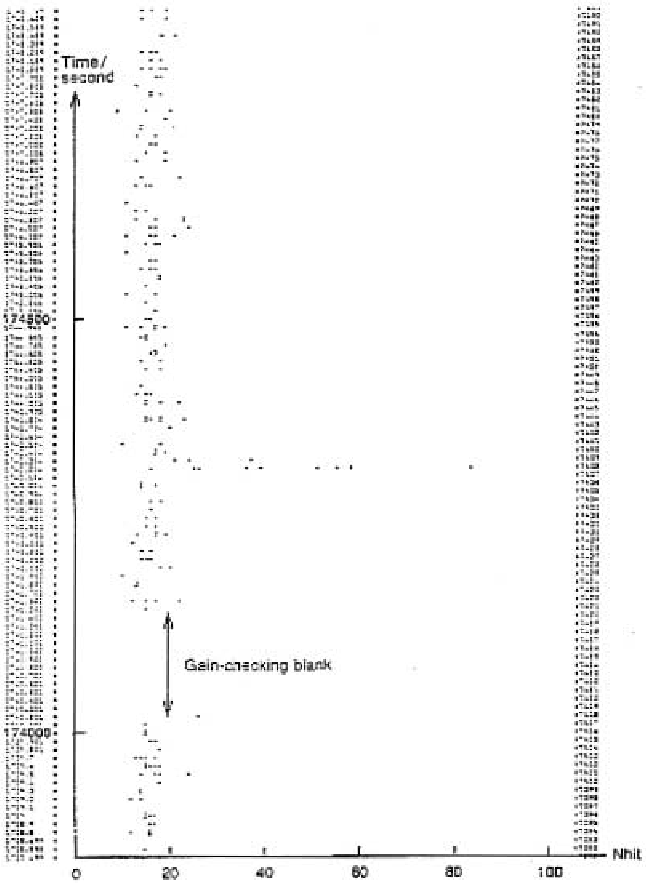


Figure 9. *The SN198TA neutino "signal" in the computer print-out.*

For instance, not only the average energy and the total number of these events agreed with the theoretical expectations, but the time duration of about ten seconds implies that the neutrinos are emitted from a very, very dense matter such as a nucleus. If the neutrinos were emitted from a tenuous stellar body, the time duration of the signal would have been less than one millisecond. But the neutrinos had to be 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 upper atmosphere 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 particles. So if everything proceeded in this way, you would get two ν_μ to one ν_e The number ratio, $N(\nu_\mu)/N(\nu_e)$ is thus two. When you go to higher energy, μ of longer lifetimes than π mesons cannot decay. Indeed, some μ 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 Figure 10 is shown the above number ratio normalized to the theoretically expected value, observed by KamiokaNDE together with the results of other experiments.

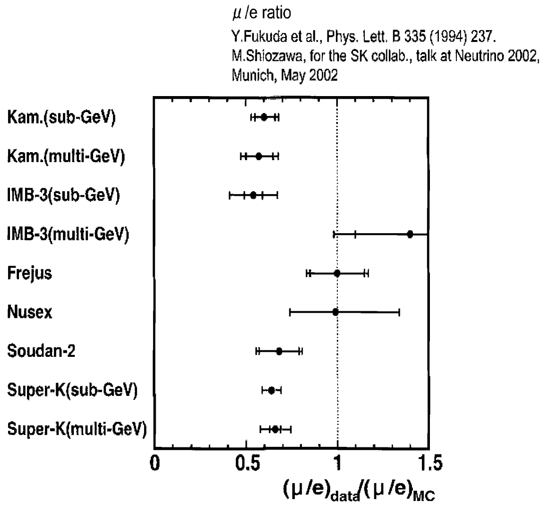


Figure 10. *The number ratio* $N(\nu_\mu)/N(\nu_e)$.

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

For the sake of simplicity, we consider that there are only two kinds of neutrinos 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. So any neutrino state can be described by a combination of ψ_{m_1} and ψ_{m_2} [Eq. (2)];

$$\psi_{\nu_\mu} = \cos\phi\,\psi_{m_1} + \sin\phi\,\psi_{m_2} \tag{2}$$

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 the m_1 state and m_2 state, with an angle parameter ϕ. The two states, ψ_{m_1} and ψ_{m_2}, 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 [Eq. (3)]:

$$E \sim p + m^2/2p \tag{3}$$

E_1 minus 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^2 difference between the two states is designated by Δm^2. When 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, ψ_{m_1} and ψ_{m_2}, induces the appearance of a 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 Figure 11 is shown the result obtained by KamiokaNDE,[10] on the atmospheric neutrino oscillation.

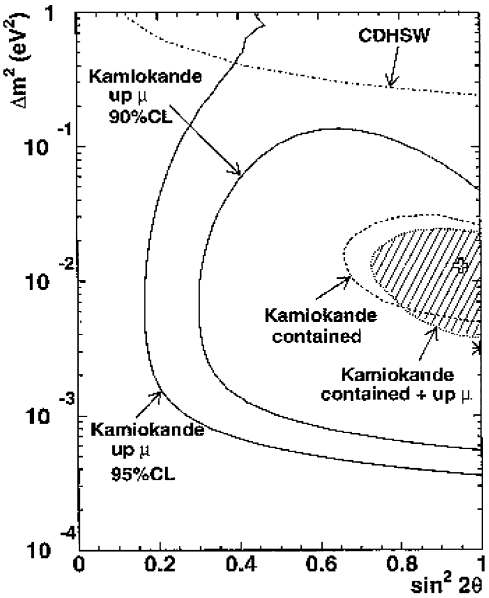


Figure 11. *The allowed parameter region.*

We now proceed to the discussion of Super-KamiokaNDE. The Super-KamiokaNDE so far produced three significant results. The first is the astrophysical observation of the solar neutrinos with sufficient statics. In Figure 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 inside the sun. In

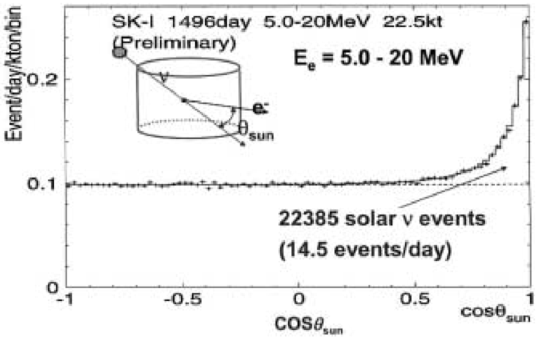


Figure 12. The directional observation.

Figure 13 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.

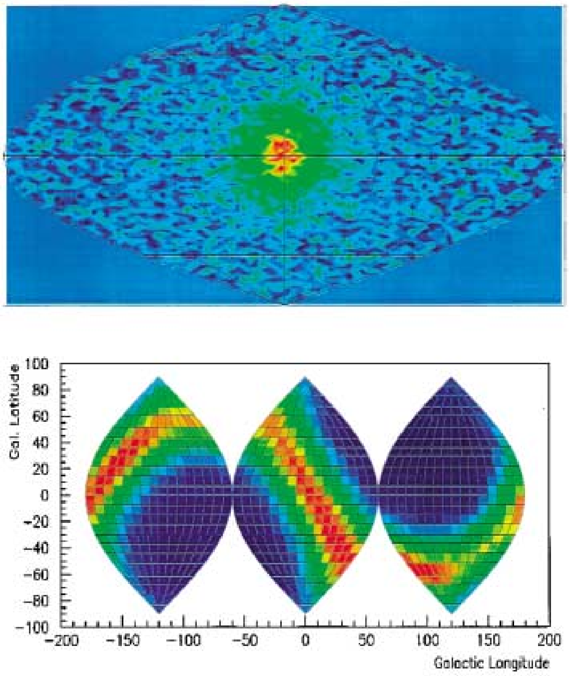
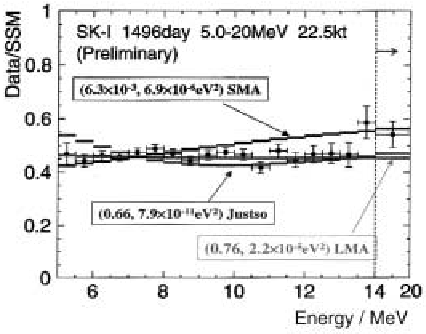


Figure 13. The neutrinograph of the Sun.

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 the sun as you see with 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 has just been born. It is still in its infantile stage.

Figure 14 shows the observation of the solar neutrino energy spectrum as compared to the theoretically expected spectrum from the solar standard model. Detailed comparison of this observed energy spectrum with the theoretical expectation gives us better information on the solar neutrino oscillation.



Bad fit for SMA and Just-so solutions.

Figure 14. The energy spectrum.

If the observed anomaly in the $N(\nu_\mu)/N(\nu_e)$ is indeed due to the neutrino oscillation, then the degree of oscillation will be different, depending on the path lengths the neutrino has to traverse from its generation to our detector. When the neutrino comes from vertically above, this path length is only 20 km; when it comes horizontally, it has traveled some 1 000 km; if it comes from below, it was produced 13 000 km away. There is a big difference in the path lengths (see Figure 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 amount of neutrinos coming from below. Only in the case of muons, you see this deficiency in the large distance direction. Figure 16 shows the allowed regions for the solar neutrino oscillation, painted yellow, and that of atmospheric neutrino oscillation, 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. Figure 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 radiochemical results.[14–17]

Now that the observed Δm^2 values are definitely not zero we have to allow some nonzero masses for the neutrinos. This implies that the Standard Theory of elementary particles has 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 ref. [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 a liquid scintillator to measure the anti-ν_e from the reactors about 200 km away. The first result from this experiment was published[18] only two days ago and I got this by e-mail.

The experiment measures the antineutrino flux as well as the energy spectrum. The result is shown in Figure 18. The obtained oscillation parameters, $\sin 2\phi = 0.833$ and $\Delta m_2 = 5.5\times10^{-5}$ eV^2, are in good agreement with the solar neutrino result of Figure 17.

Since this is a confirmation of the neutrino oscillation not for the electron neutrino but for the antielectron neutrino, the fact that it gives the same oscillation parameters implies that the CPT (C: charge, P: parity, T: time reversal) theorem is not violated.

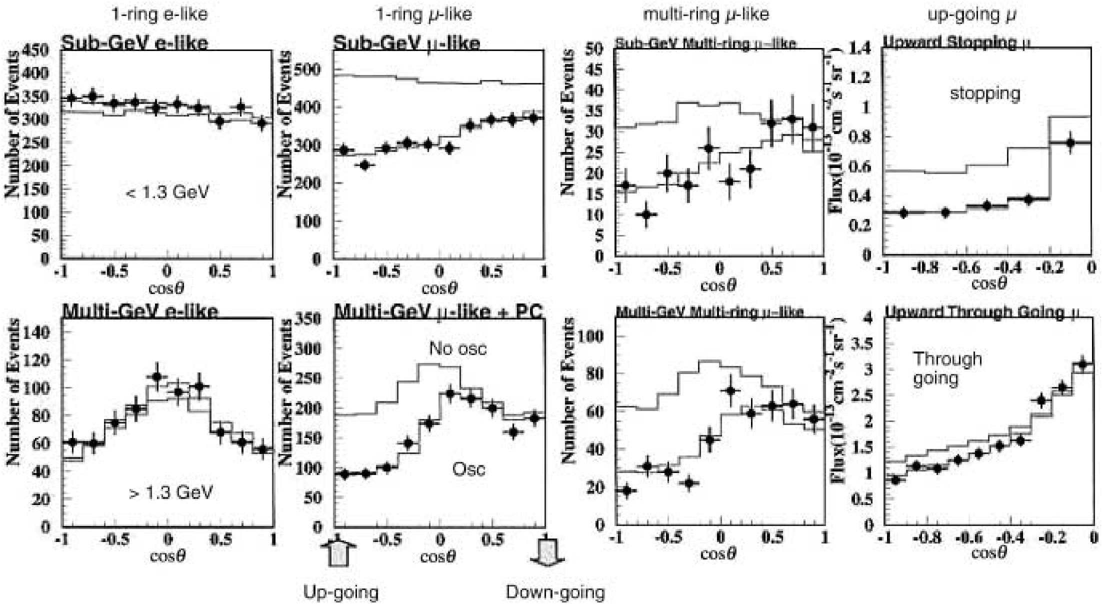


Figure 15. *The change of oscillation as a function of path length.*

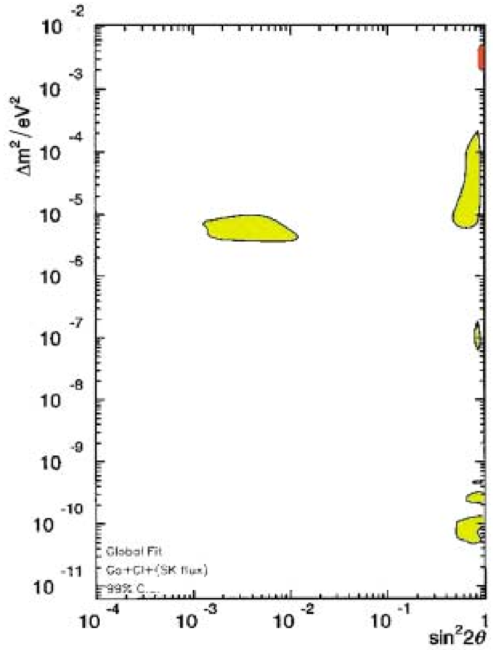


Figure 16. *The allowed regions of oscillations.*

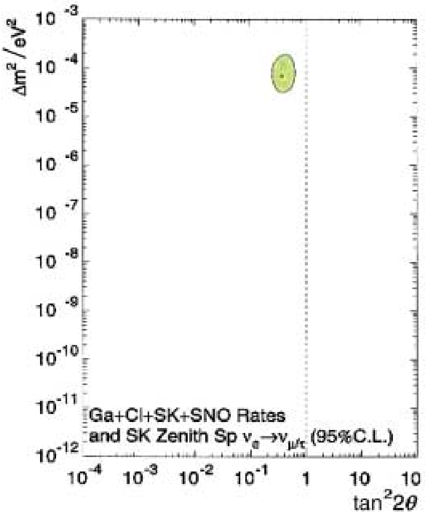


Figure 17. *The allowed region for the solar neutrino oscillation.*

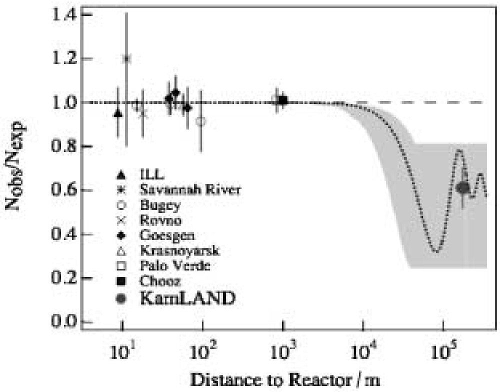


Figure 18. *Recent results from KamLAND.*

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 ref. [18]. The interesting thing is that about two-thirds of the collaborators are from the United States. Some say Kamioka is now considered to be the "Mecca" for neutrino research and this pleases me very much.

Now that neutrino astrophysics has been 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-KamiokaNDEs may be a good choice for supernova watching. The most challenging problem will be the observation of the cosmic neutrino background (CNB) of 1.9 K, which would tell us the state of our universe one second after its birth. The nonzero masses of neutrinos imply the total reflection at low temperature of low energy neutrinos. This is a wonderful gift, providing the possibility of a parabolic mirror for focusing CNB. The detection, however, of such low energy neutrinos is really a formidable task.

It is my pleasure to acknowledge the technical contribution of Hamamatsu Photonics Co. for producing the 50 cm ϕ 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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