Eur. Phys. J. H **37**, 33–73 (2012)
DOI: 10.1140/epjh/e2012-30007-y

THE EUROPEAN
PHYSICAL JOURNAL H

On the origin of the Kamiokande experiment and neutrino astrophysics

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Received 10 February 2012 / Received in final form 19 March 2012
Published online 22 May 2012

Abstract. The Kamiokande experiment was originally conceived and designed for the detection of proton decay signals. In the early stage of the experiment, it was decided to upgrade the detector so that astrophysical neutrinos including solar neutrinos in the 10 MeV energy range can be detected. When the upgrade of the detector was almost completed, a neutrino burst from Supernova SN1987A was detected. 2 years later, solar neutrinos were also observed with the energy, the directional and the arrival time information. This article describes the story of the Kamiokande experiment, and the subsequent development of the neutrino physics, including the neutrino oscillation, and astrophysics with Kamiokande and its successors; Super-Kamiokande and KamLAND.

1 Initial idea of Kamiokande

In the 1970's, the idea of Grand Unified Theories of strong, weak and electromagnetic interactions emerged [1, 2]. These theories predicted nucleon decays with a typical lifetime of 10^{30} years, with about 2 orders of magnitude uncertainty in its prediction. If the nucleon lifetime is less than 10^{32} years, it should be possible to observe proton and bound neutron decays by a massive detector with the mass of the order of 1 kilo-ton.

A workshop on "The Unified Theory and the Baryon Number in the Universe" was held in KEK in 1979.

H. Sugawara who was one of the organizers of this workshop made a phone call in late 1978 to M. Koshiba, asking a talk on a possible proton decay experiment. Immediately, M. Koshiba recalled a discussion with G. Occhialini many years ago on an underground experiment using clean water. M. Koshiba proposed the initial concept of Kamiokande, which was a water Cherenkov detector. A charged particle propagating in a medium with a speed exceeding the speed of light in the medium emits Cherenkov radiation (light). The speed of light in a medium is (c/n), where c

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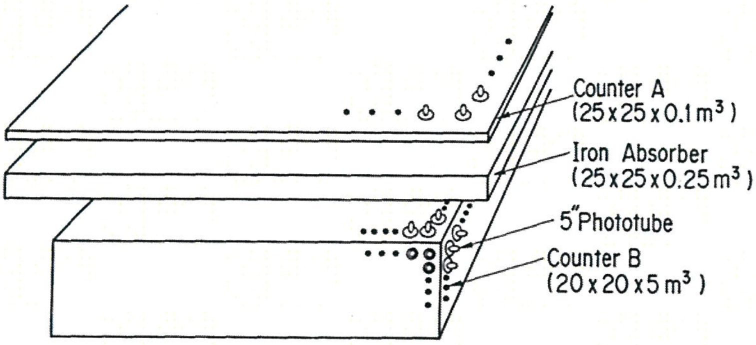

Fig. 1. Initial idea of the Kamiokande detector, which was presented at "the Unified Theory and the Baryon Number in the Universe" held in KEK in 1979 [3].

is the speed of light in the vacuum, and n is the refractive index of the medium. The refractive index for water is approximately 1.34. Cherenkov radiation is radiated only to a direction defined by $\cos\theta = 1/(n\beta)$, where θ is the angle that Cherenkov photons are emitted relative to the direction of the particle motion, and β is the velocity of the particle relative to the light velocity in the vacuum. In water, a highly relativistic particle with the velocity very close to c (namely, β very close to 1) thus emits Cherenkov light in the direction of about 42 degrees from the direction of the particle motion. The Cherenkov light can be detected by photon counters, such as photomultiplier tubes (PMTs).

The proposed detector is shown in Figure 1. Unfortunately, M. Koshiba caught a cold just before the workshop. Therefore, his idea was presented by a member of his research group (Y. Watanabe) at the workshop [3]. It comprised water Cerenkov counters A and B, and was assumed to be located deep underground. Counter B was planned to be used to detect nucleon decay which occurred in water within the detector. The proposed size was $20 \times 20 \times 5$ m^3, containing 2000 ton of water. The counter surface was to be covered with 7500 5-inch diameter PMTs, one in every 40×40 cm^2. The inside of the counter wall was painted black so as to avoid any reflection of the Cerenkov light: thus the direction and the energy of charged particles can be measured. Counter A, which served as a counter to identify atmospheric muon backgrounds that penetrated through the detector, had a size of $25 \times 25 \times 0.1$ m^3, and was placed above counter B. Hereafter, a counter or a detector that is used to reject background events is called a "veto-counter". The inside of this veto-counter was painted white, and the water was dissolved with a wavelength shifter, which absorbs ultraviolet light and reemits blue light, so as to increase the light yield, thus reducing the number of necessary PMTs: one hundred PMTs might have been more than enough. These were pasted onto the top surface of the counter. A steel plate having a thickness 25 cm between counters A and B was used to stop any charged particles produced by nucleon decays in counter B. Figure 2 illustrates how the $p \to \mu^+ + \gamma$ decay would be detected in this detector.

However, this detector required a huge amount of funding, since it should have required nearly ten thousand PMTs. Hence M. Koshiba thought of making a cubic detector containing 3000 ton of water and surrounded by 1000 5-inch diameter PMTs. The proposed detector was approved and partially funded by the Ministry of Education. The news then came from USA that an 8000 ton water Cerenkov detector surrounded by 2000 5-inch diameter PMTs was proposed. This was obviously much better than the proposed detector by M. Koshiba as far as the sensitive volume for proton decay was concerned. At this stage the Ministry of Education would not approve

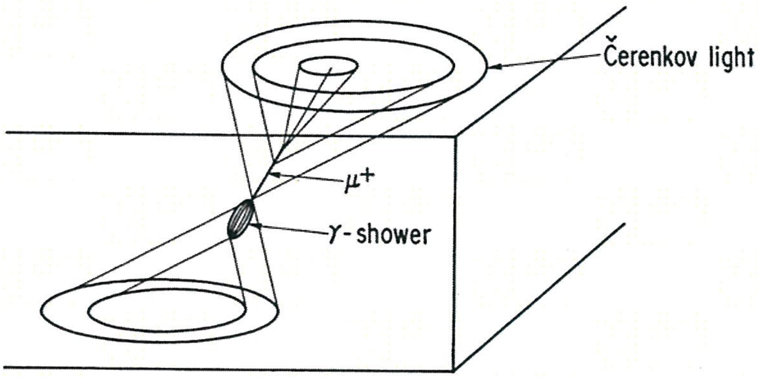

Fig. 2. Image of the proton decay into $\mu^+ + \gamma$ in the detector illustrated Figure 1. Cherenkov photons emitted by the muon and an electromagnetic shower initiated by the γ are detected by the PMTs instrumented at the inner surfaces of the detector. The Cherenkov photons emitted by each particle is recognized as a "Cherenkov-ring".

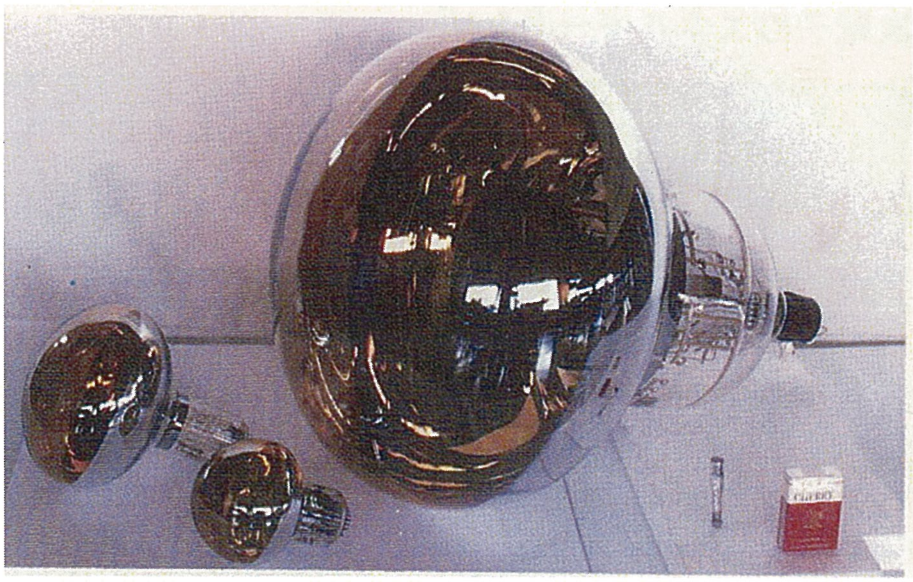

Fig. 3. Photograph of a 20-inch diameter PMT, compared with 1/2, 5 and 8-inch PMTs.

any increase of funding. How could we resolve this difficulty within the approved budget? Since we could not increase the number of PMTs the only possible way-out was to increase the sensitivity of each PMT by increasing the photocathode area.

In 1979, M. Koshiba discussed with T. Hiruma who was the president of Hamamatsu TV Co., Ltd. (its present name is Hamamatsu Photonics Co., Ltd.), which was one of the companies that was able to produce high quality PMTs. At the end of the discussion, T. Hiruma agreed to develop large PMTs jointly with the University of Tokyo group. M. Koshiba obtained 100 M yen developing fund from the Ministry of Education. In 1981, the 20-inch diameter PMT became a reality [4]. The 20-inch PMTs were confirmed to have sufficiently good characteristics as the detector component of the experiment, and the mass-production was established [5]. Figure 3 shows a photograph of the 20-inch PMT, compared with 1/2, 5 and 8-inch PMTs.

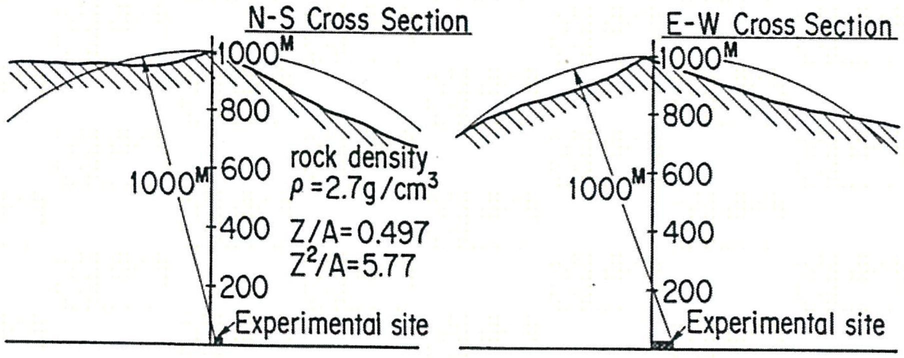

Fig. 4. Location of Kamiokande under the Ikenoyama mountain. There was a horizontal tunnel with a rail-track which was used to access to the site.

2 Design of the Kamiokande detector

In the early stage of designing of the 3000-ton water Cerenkov detector equipped with 1000 newly developed 20-inch PMTs, a cubic detector which was entirely surrounded by a 1 m depth of veto-counter was considered. However, in terms of the stability of the underground cavity, a cylindrical-shape cavity was preferred. Consequently, the detector shape was changed to cylindrical.

Another important issue was the selection of the underground site. In order to reduce the cosmic ray background, the detector should be located deep underground. From a consideration of the cosmic ray muon rate, a depth of approximately 1 km from the surface was required. In addition, the rock condition must be good enough to excavate a large cavity. Other factors to be considered were; the availability of the clean water to be used as the primary water for the detector, the easy access, the understanding of the mine company that operates the underground site. In the 1960's, M. Koshiba, together with T. Suda and Y. Totsuka, carried out an underground cosmic ray experiment [6, 7] at the Kamioka mine, and therefore, the Kamioka mine was one of the candidate sites. The experimental site was indeed determined to be at the Kamioka mine located in Gifu Prefecture in Central Japan, 220 km north-west of Tokyo. This experiment was named Kamiokande after KAMIOKA Nucleon Decay Experiment.

This mine was actively producing zinc and lead. The underground laboratory was located below the top of a mountain at the depth of 1000 m (see Fig. 4). The average rock density was 2.7 g/cm^3; thus the average rock overburden was approximately 2700 meters water equivalent (mwe). This site had many desirable functions. The rock was very solid and stable, and showed no potential hazards with water or air. Well-maintained horizontal access tunnel with the rail-track led to the site. A stream of clean natural water of about 2 tons/min with 9 °C and $PH = 7.8$ was available along the tunnel. The temperature in the tunnel was about 13 °C all the year around, while the relative humidity was approximately 93%.

A steel tank of a cylindrical shape of 15.5 m in diameter and 16 m in height was constructed. The total water volume was 3000 m^3. Figure 5 depicts the Kamiokande detector. Ring images of Cherenkov radiation were detected by a total of 1000 20-inch PMTs which were instrumented on the inner walls of the tank in the form of a matrix array of 1 PMT/m^2; 20% of the tank's wall was covered by photosensitive cathodes. This offered a good energy resolution, approximately 4%, for an 1 GeV electron shower. Consequently a good background rejection and good identification of various modes of nucleon decays were expected. Figure 6a shows a typical example

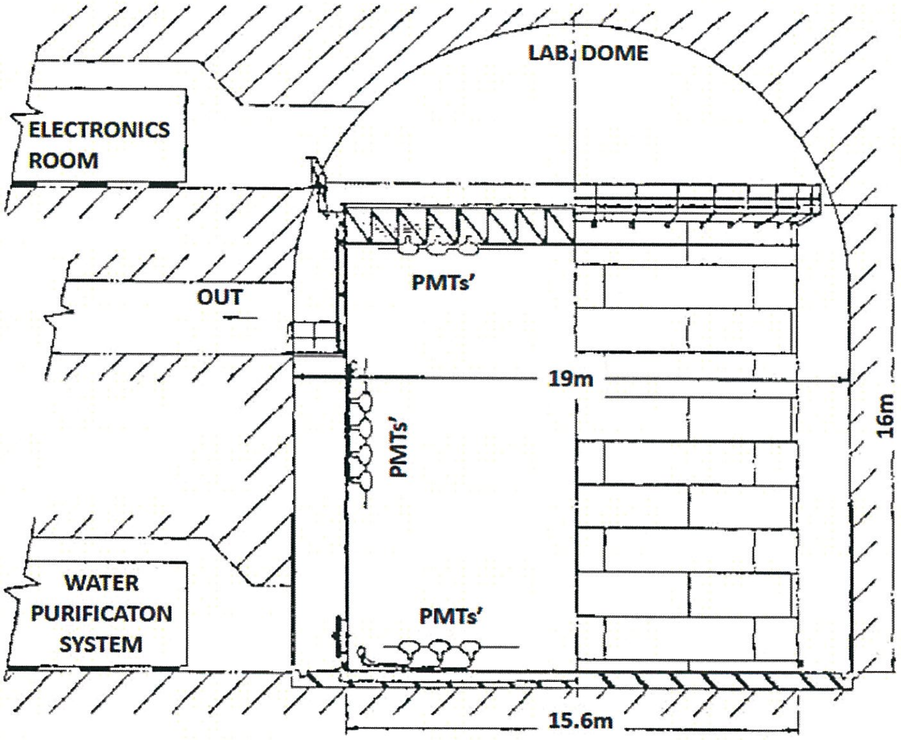

Fig. 5. The Kamiokande detector in the first stage.

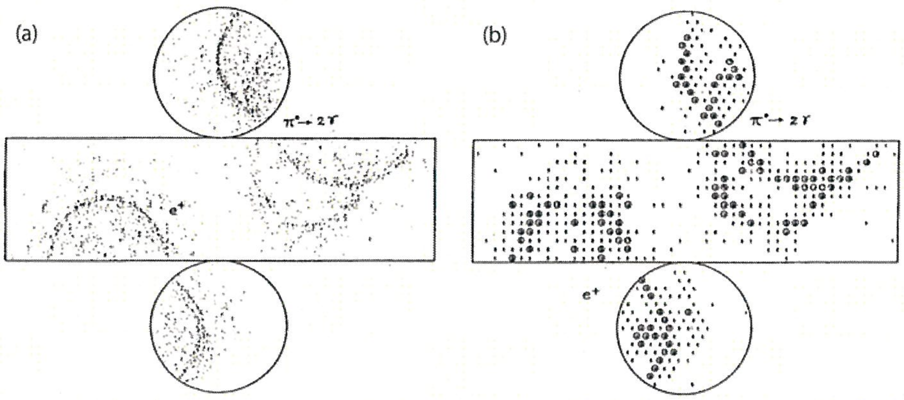

Fig. 6. (a) Typical example of simulated Cherenkov-ring pattern appearing on the inner walls of the tank for a proton decay into $e^+\pi^0$. (b) The response of the PMT array for this event. PMTs that observed more than 4 photo-electrons are marked by circles.

of a simulated Cherenkov-ring pattern for the $p \to e^+\pi^0$ decay. The response of the PMT array for this event is shown in Figure 6b. The numbers indicated in the figure shows the number photo-electrons, namely the number of electrons emitted by the photo-cathode when photons hit the photo-cathode. The characteristic Cerenkov-ring patterns can be clearly recognized when the tubes with more than 4 photoelectrons are selected as shown by circles (see Fig. 6b). The design and the preparation status of

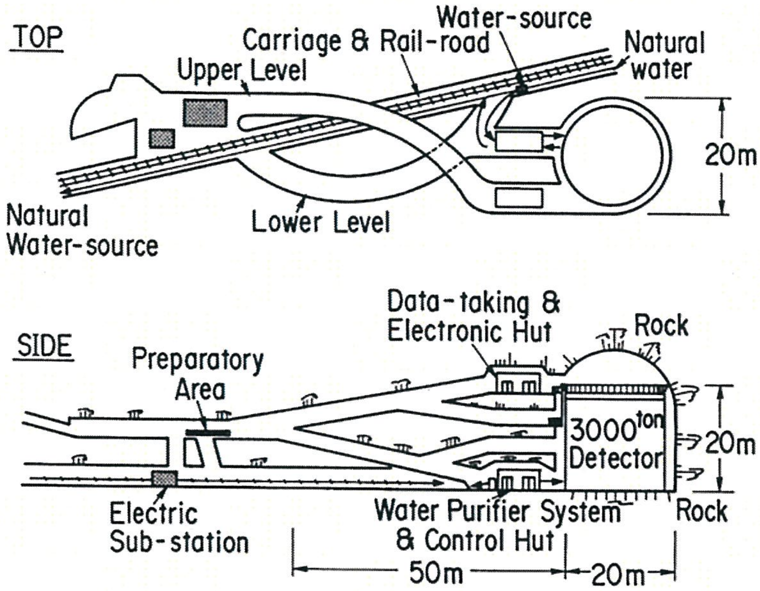

Fig. 7. Schematic view of the entire experimental area of Kamiokande.

the 3000-ton water Cherenkov detector were first presented at the 1981 International Conference on Neutrino Physics and Astrophysics (Neutrino '81) [8]. The status of Kamiokande at this stage is also reported in [9–11]. Various scientific possibilities with the Kamiokande detector was discussed in the proposal of this experiment [12].

3 Construction of the Kamiokande detector

The excavation of the large-volume cavity (19 m diameter, 23 m high at the center and 20 m high at the edges) started at the beginning of 1982. It took about 10 months to complete the excavation. A schematic view of the entire experimental area is shown in Figure 7. The flat spaces of the tunnels near to the cavity were used for the data-taking electronics room at the top and for the water purification system at the bottom. The construction of the 3000-ton water tank followed immediately after the cavity excavation, and continued until March, 1983. The steel was 12 mm thick at the bottom. The thickness was gradually reduced toward the top, and was 4.5 mm thick at the top. The inner surface of the tank was painted black to a thickness of 250 μm with a specially selected epoxy, suitable paint for pure water. The construction of the water-purification system and the data-taking electronics system began in early 1983. All of the necessary instruments were delivered to the mine by the end of March, 1983. During detector construction, 1000 20-inch PMTs were delivered to the mine from various storage places.

The installation of 1000 PMTs into the tank began in April, 1983. It took approximately three methods to install the PMTs into the detector tank. At first, the PMTs in the bottom plane and the lowest two side rows were mounted to the support frame by hand. At this stage, a problem in the cable connection was revealed. A substantial fraction of the high-voltage cables were short-circuited. Fortunately, the problem was fixed within a week. Water was then poured into the tank, and the installation of the side wall PMTs was carried out on floating rubber boats. The water was leveled up after completing every 48 tubes in one row on the side wall. It took two working

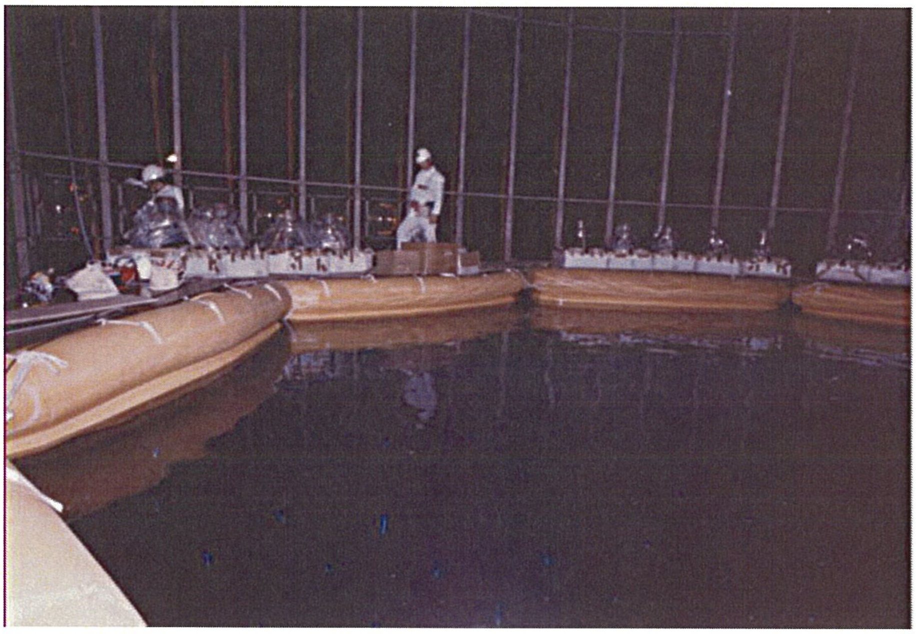

Fig. 8. PMT installation on the side wall of the detector. The PMTs were installed to the framework on the detector wall by the collaborators of Kamiokande using rubber boats on the water.

days to install 48 PMTs. Finally, the PMTs at the top plane, which comprised a 3-PMT-module, were installed using a crane. A photograph taken during PMT installation on the side wall is shown in Figure 8. The detector was ready in early July, 1983.

4 Start of the Kamiokande experiment

The Kamiokande experiment started on July 6, 1983. In July and August, much time was spent to examine the detector performance and to develop analysis programs for events such as nucleon-decays and atmospheric neutrinos. Data tapes were regularly sent from Kamioka to the Univ. of Tokyo. The computer system at ICEPP (International Center for Elementary Particle Physics) of the Univ. of Tokyo was fully utilized for the data analysis. On Sept. 17, 1983, the first candidate event of nucleon decay was observed. Figure 9 shows the visual display of this event, in which the cylindrical detector is opened to flat. The area of each circle is proportional to the number of photo-electrons detected by the PMT. Three well-separated Cherenkov rings were clearly seen. A Transit Digitizer, which was used to record the wave form of the analog sum of the 1000 PMTs' signal, recorded a small second pulse, which was consistent with the one from a $\mu \rightarrow \mathrm{e}$ decay, as shown in the lower-right of Figure 9. The curves in this figure showed the results of a fit, which assumed a common vertex for the rings. This event was interpreted as a candidate nucleon decay in the modes of $p \rightarrow \mu^+\eta$ $(\eta \rightarrow \gamma\gamma)$, $p \rightarrow \mu^+\mathrm{K}^0$ $(\mathrm{K}^0 \rightarrow \pi^0\pi^0)$ or $n \rightarrow \mathrm{e}^+\rho^-$. The observation of this event stimulated the search for nucleon decays. Several more candidate events were observed. However, these additional candidate events were not as distinct as the first one. Initial results from Kamiokande can be found in [13]. Initial results on nucleon decay searches were reported in [14, 15].

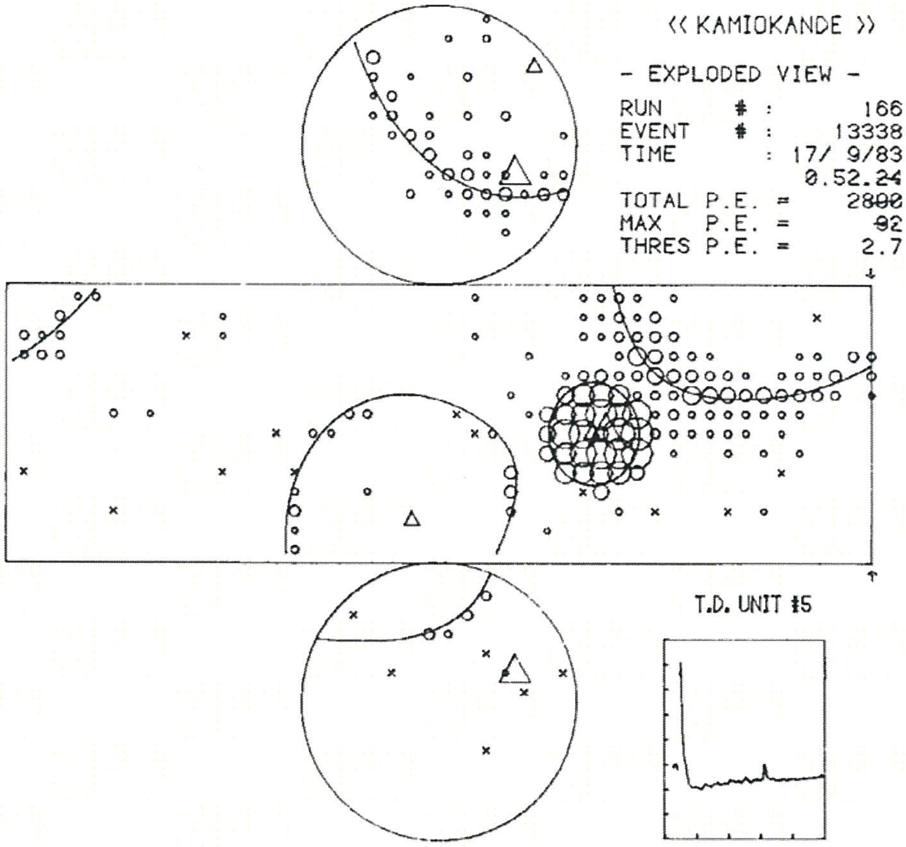

Fig. 9. The first candidate proton decay event observed in Kamiokande. The area of each circle is proportional to the number of photo-electrons detected by the PMT.

5 Idea of Kamiokande-II

Even before the start of the experiment, M. Koshiba had been thinking that the Kamiokande experiment should produce significant scientific results, even if proton decays were not observed. M. Koshiba thought that this was the duty of a scientist who spent a lot of budget, which was originally the tax of the nation. In the autumn of 1983, which was only several months later since the start of the Kamiokande experiment, M. Koshiba pointed out a possibility of detecting ^{8}B solar neutrinos by observing an electron produced by a neutrino-electron scattering; $\nu e \rightarrow \nu e$. This idea appeared by observing a pulse-height distribution of electrons from decays of stopping cosmic-ray muons ($\mu^{\pm} \rightarrow e^{\pm}\nu_\mu\nu_e$). Electrons from muon decays have an energy spectrum up to 53 MeV. Figure 10 shows the energy spectrum of these electrons observed in Kamiokande. One can see that the energy spectrum, which was consistent with the expected one, reached down to 15 MeV. Below this energy, the spectrum was dominated by background events. This figure implied that it must be possible to detect ^{8}B solar neutrinos with a maximum energy of 14 MeV by reducing background events. This observation motivated the upgrade of the Kamiokande detector.

Solar neutrinos give direct information on the fusion processes in the Sun. Therefore solar neutrino experiments are unique as a probe of the solar interior. Before Kamiokande, there was only one experiment that observed solar neutrinos. It was

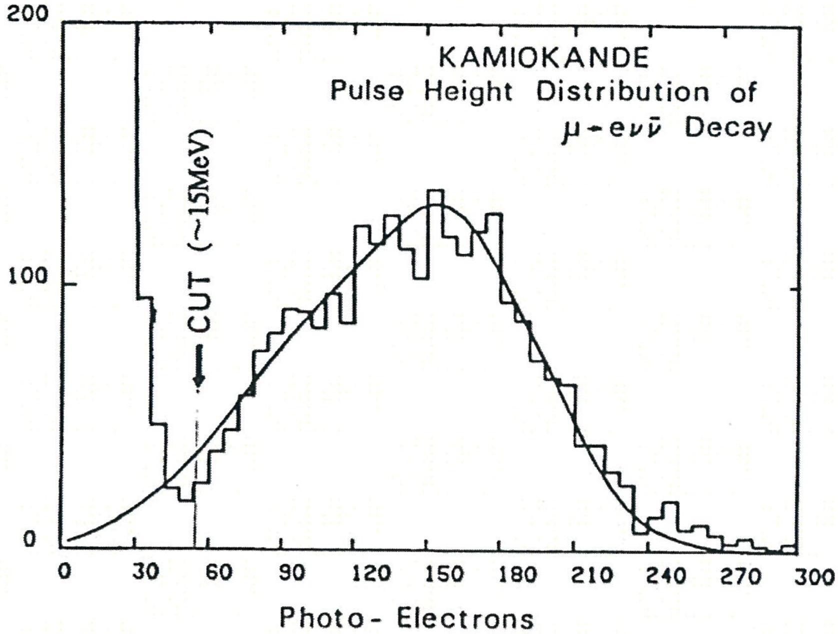

Fig. 10. Observed energy spectrum of electrons produced by decays of stopping cosmic-ray muons in the detector.

the Homestake solar neutrino experiment, led by R. Davis Jr. In the late 1960's, this experiment started to observe solar neutrinos [16]. The observed flux, however, was approximately 30% of the prediction by the standard solar model. Many possibilities were discussed on the origin of the solar neutrino deficit: is the experiment wrong? Is something wrong in the model of the Sun? Is something wrong in the understanding of particle physics? Therefore, a large effort went into checking the Homestake experiment and proposing new experiments that can measure *pp* solar neutrinos whose flux is much less sensitive to the details of the solar model. An important contribution came from the GALLEX [17] and SAGE [18] experiments, which measured sub-MeV solar neutrinos in the 1990's.

Detecting solar neutrinos in a water Cherenkov detector by neutrino-electron scattering has several unique features compared with the radiochemical method utilized in the Homestake experiment. A water Cherenkov detector can get the information on the neutrino arrival direction, confirming that neutrinos are indeed coming from the Sun. It can measure the energy spectrum, which makes it possible to study a particular nuclear reaction in the nuclear fusion chain in the Sun. Finally, the Cherenkov detector is a real time experiment, and this feature makes it possible to make various studies on the time variation.

At ICOBAN'84 (International Conference On BAryon Non-conservation, Park City, Utah, 1984), M. Koshiba gave a talk on the possibility to detect ^{8}B solar neutrinos in Kamiokande [19]. He asked the attendants to collaborate for upgrading the Kamiokande detector for the solar neutrino detection. Soon after this workshop, A.K. Mann of the Univ. of Pennsylvania expressed their interest in the collaboration in Kamiokande, and proposed to prepare a new electronics system with dead-time-free time and pulseheight (charge) measurement for each PMT. The first meeting with the US group was held in Tokyo in March, 1984. The delegates from the US group included A.K. Mann, E.W. Beier and R. Van Berg from Univ. of Pennsylvania, B. Cortez from Caltech, and D.H. White from BNL.

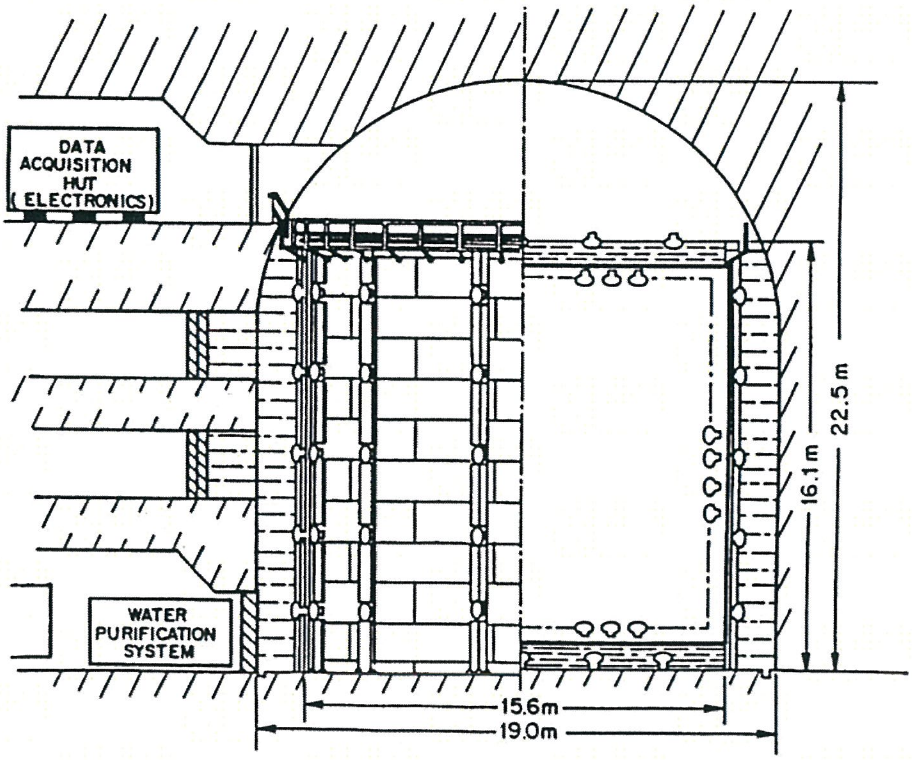

Fig. 11. Schematic view of the Kamiokande-II detector. The top and bottom veto-counters were constructed in the steel tank, while the side veto-counter was constructed by filling the space between the tank and the surrounding rock with the mine water.

6 Design of the Kamiokande-II detector

The design of the upgraded Kamiokande detector was investigated until July, 1984. Kamiokande was upgraded to Kamiokande-II. The main new features were the upgraded electronics system with the deadtime free pulse-height (charge) and time measurement, a 4π solid-angle veto-counter system, and the improved water purification system. Figure 11 shows a schematic view of the Kamiokande-II detector. 1071 20-inch PMTs (948 for the inner counter and 123 for the outer vetocounter) were mounted on the detector walls. The top, side and bottom veto-counter layers were 0.7 m, 1.5 m and 1.2 m thick, respectively. These active water layers shielded against entering photons and neutrons, and identified entering cosmic-ray muons. In order to construct the bottom veto-counter, 48 inner PMTs at the lowest row had been removed. Then the entire bottom PMTs together with the support structure were lifted up by 1.2 m. There were 3 access tunnels to the tank, which should be closed for the construction of the side veto-counter. The outer wall of the tank and the cavity wall that formed the water enclosure for the side veto-counter were sprayed with a water-tight rubber-asphalt. The entire surface of the veto-counter sections was covered by aluminum polyethylene-coated sheets for reflectivity.

The work toward the detector upgrade began in Sept., 1984. Simultaneously 30 dead PMTs were replaced by new ones while removing detector water (see Fig. 12). This was the first time that the inside of the detector was investigated after starting the experiment. Overall, the condition of the detector was found to be kept good.

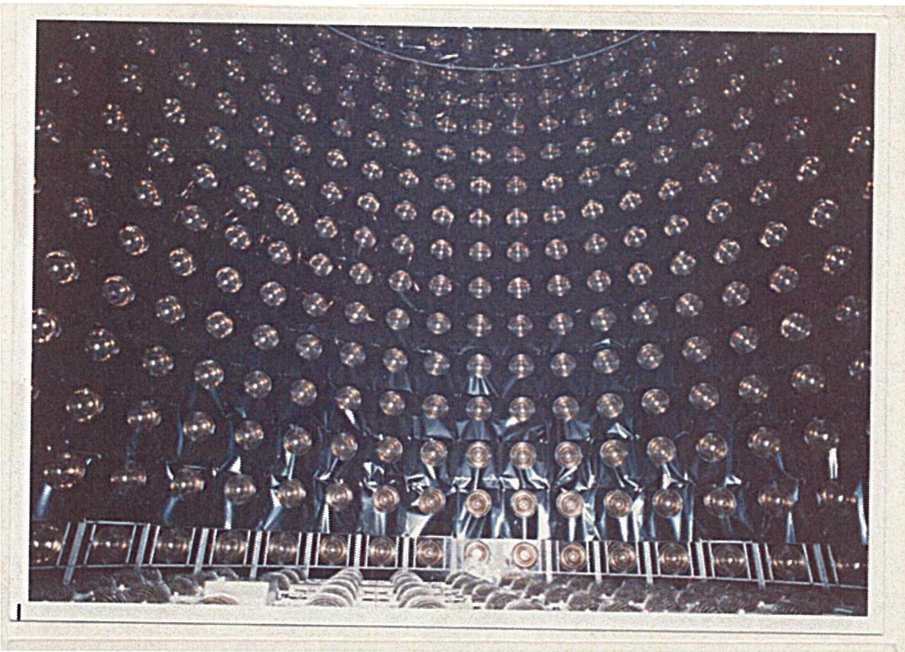

Fig. 12. A photograph that was taken when the dead PMTs in the Kamiokande detector were replaced with new ones. In this photo, black sheets surrounding the PMTs at the bottom of the side wall were already removed in order to remove these PMTs. After the removal of these PMTs, the PMTs at the bottom plane were lifted up by 1.2 m in order to construct the bottom veto-counter below the PMT plane.

The construction of the top and bottom veto-counter layers was completed by the middle of December, 1984. Water was refilled into the detector tank.

The access tunnels were shielded by thick concrete walls for constructing the side veto-counter. Then a rubber-asphalt was sprayed to the rock wall for the water tightness. Subsequently, filling water into the side veto-counter started. Soon after starting the filling, a water leak from the surrounding rock wall was found. This was caused by many regions of unevenness on the rock wall, thus making a water-tight coating incomplete. Although spraying rubber-asphalt was retried many times, finally the complete water-tightness was given up. Instead filled water by a high-power pump was adopted so as to overcome the water leak. Due to this problem, completion of the side veto-counter was delayed to March, 1985. The side veto-counter PMTs were installed by suspending each array of PMTs from the top of the water tank. Figure 13 shows the construction work of the side veto-counter.

In the initial stage of Kamiokande fresh water, which flows continuously in the mine tunnel, was supplied into the tank. However, it was found that natural water contained much ^{222}Rn (200 pCi (pico-Curie) per liter), which was one of the major background sources for the solar-neutrino detection. The half lifetime of ^{222}Rn is 3.8 days. In March 1985, it was found that the trigger rate with the threshold of 8.5 MeV was 500 Hz. It was also found that the trigger rate dropped when the water purification system was stopped (see Fig. 14). The speed for the trigger rate drop was consistent with the decay of ^{222}Rn. Hence, from the beginning of April 1985, the water for the inner-detector was re-circulated after passing through the water purification system. Improvements of the water purification system in Kamiokande-II are described in the next section.

Fig. 13. Construction of the side veto-counter. PMTs for the side veto-counter were prepared at the bottom, and hanged from the top. All the surfaces of the veto-counter volume were covered by the aluminum polyethylene-coated sheets for reflectivity.

The electronics system was modified in Kamiokande-II (see Fig. 15). Signals from the PMTs were connected to the new electronics system developed by the Pennsylvania group. Each PMT signal was split into two. One signal went through a buffer amplifier and then into the original Kamiokande electronics. The other signal went into the new electronics. The new electronics system was ready in November, 1985. They included charge and timing measurement systems with multi-depth analog buffers. The timing information provided a remarkable improvement in the vertex reconstruction, especially for events in the energy range of solar neutrinos. For example, the accuracies of the position and direction reconstructions for a 10 MeV electron were 1.7 m and 28 degrees, respectively. Kamiokande-II data-taking started in December, 1985.

7 Toward the solar neutrino detection

To observe ^{8}B solar neutrinos it was necessary to lower the detection threshold energy, at least down to 10 MeV. However, there were various background sources that produced electrons and γ's in the 10 MeV or lower energy range in the detector. The environmental background events of γ's and neutrons from the surrounding rock were

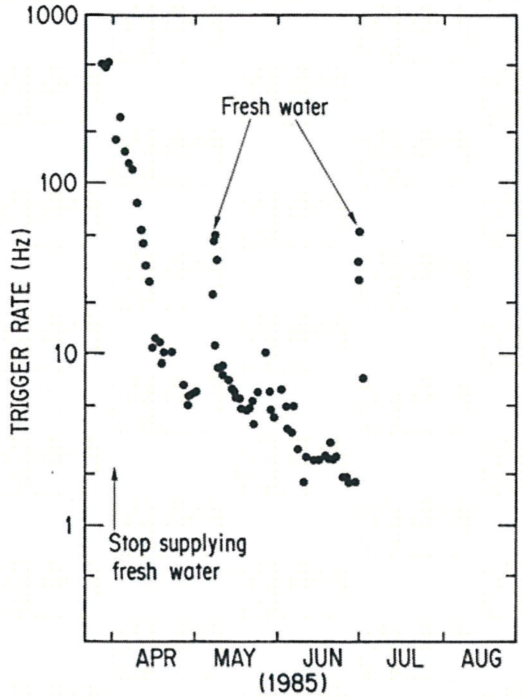

Fig. 14. Trigger rate with the threshold of 8.5 MeV as a function of time in 1985.

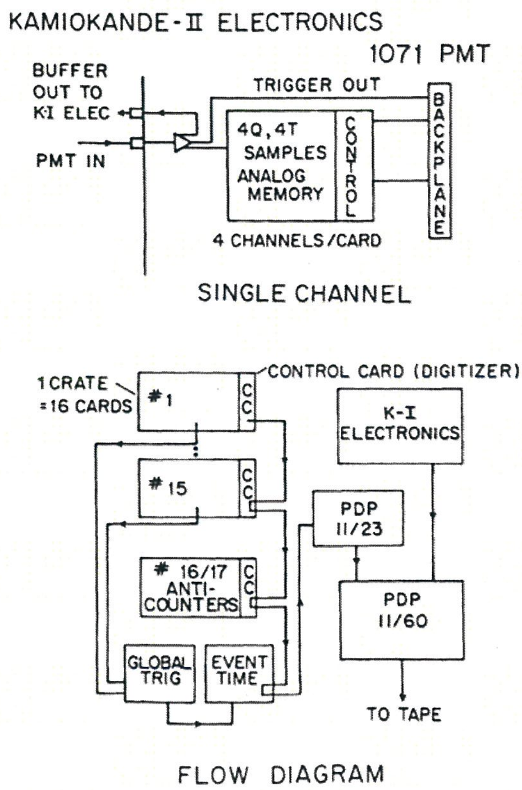

Fig. 15. Block diagram of the Kamiokande-II electronics.

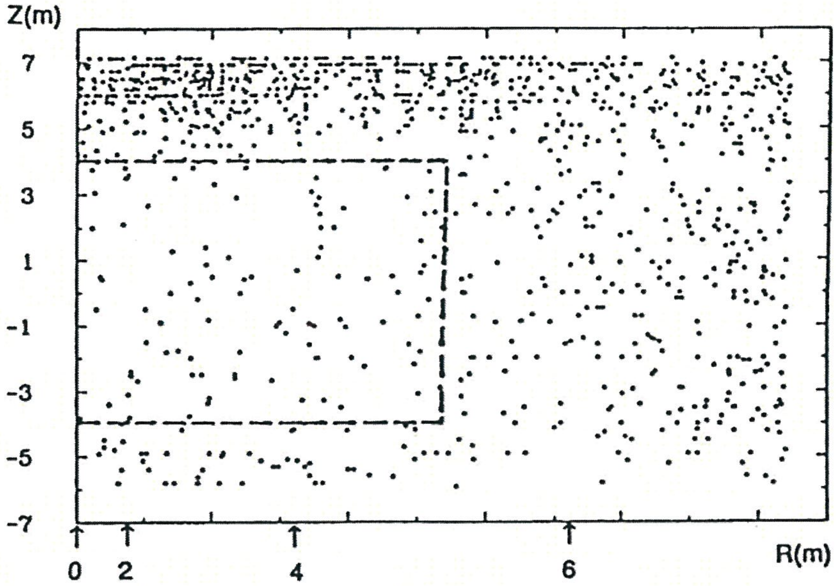

Fig. 16. Vertex point distribution for the reconstructed events in the 10 MeV energy range in the R-Z plane, where R and Z stand for the radial and height coordinates in the cylindrical detector. The data were from the early stage of the Kamiokande-II experiment. The top and bottom PMT planes were located at $Z = +7.14$ and -5.98 m, respectively. The side PMT wall was located at $R = 7.22$ m.

attenuated, owing to the veto-counter water layer. Surviving events passing through the veto-counter were largely rejected by requiring that the reconstructed vertex position should be located within a fiducial volume. Figure 16 shows the vertex point distribution for the reconstructed events, in the R-Z plane, where R and Z stand for the radial and height coordinates in the cylindrical detector, respectively. The concentration of events can be seen near to the detector walls. In addition, higher concentration of events can be seen near to the top detector wall, probably due to the thinner veto-counter at the top. The fiducial volume for the solar neutrino analysis was set in the region of -3.98 m $\leqq Z \leqq 4.0$ m and $R \leqq 5.22$ m, which was 2 m from the side and bottom PMT walls and 3.14 m from the top PMT wall, corresponding to a total fiducial volume of 680 m^3.

Other serious background sources came from interactions of high-energy cosmic-ray muons in the detector, where muons break up ^{16}O and produce various radioactive nuclei. These cosmic-ray muon-induced events were eliminated only by off-line data analyses, using the spatial correlation between the muon traversing path and the vertex positions of the subsequent electrons, the timing correlation between the preceding muons and the electrons, and the deposit energy of the muons.

The fission products of ^{238}U and ^{232}Th, as well as β-rays and γ-rays from radioactive nuclei in the decay series of ^{238}U and ^{232}Th were also dominant background sources. In the spontaneous fission of uranium, prompt energy is released in the form of γ-rays with the total energy of approximately 7 MeV, and the mean number of γ-rays is about 7.4. β-rays with $E_{\max} = 3.26$ MeV emitted from ^{214}Bi in the $^{226}Ra \rightarrow {}^{222}Rn \rightarrow \ldots \rightarrow {}^{214}Bi \rightarrow {}^{214}Po$ decay chain were a serious background source, since ^{226}Ra and ^{222}Rn were contaminated in the detector water. Moreover, the content of ^{222}Rn in the mine air was approximately 10^2–10^3 times higher than that of air outside of the mine. The mine air was always in contact with the detector water

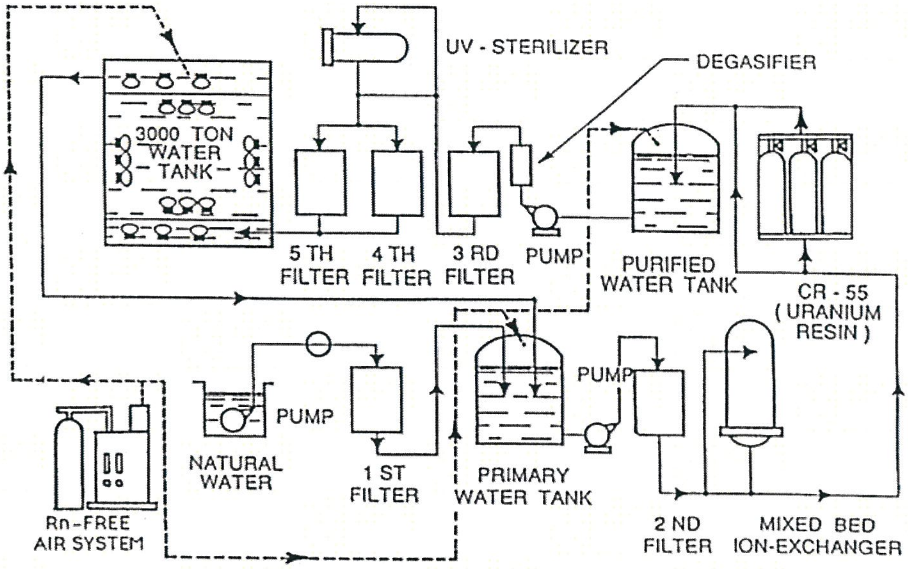

Fig. 17. Block diagram of the water purification system in Kamiokande-II.

at the top surface of the 3000 m^3 tank and two buffer tanks in the water purification system. The improvement in the water-purification system was directed so as to remove the radioactive materials discussed here. Figure 17 shows the water purification system in Kamiokande-II.

A normal ion-exchanger is effective for absorbing all types of ions dissolved in water. However, the efficiency strongly depends on the concentration of other ions. Amidoxime group chelete resins have the property to selectively adsorb uranium in water. The efficiency was measured to be above 90% for the Kamioka mine water. The ion-exchanger with amidoxime resins was installed in March, 1986. ^{232}Th and ^{226}Ra are expected to be removed by the usual type mixed-bed (anion+cation) ion-exchanger. A new mixed-bed ion-exchanger was installed in Sep., 1986. The change in the contents of ^{238}U and ^{226}Ra after operating the ion-exchangers is shown in Figure 18.

As written above, fresh water was always supplied from the mine into the detector in Kamiokande-I, since cool mine water (approximately 9 °C) is effective for suppressing bacteria growing in the detector. On the other hand, the detector suffered from a high radon concentration due to the fresh water. Figure 19 shows the annual variation in the ^{222}Rn concentration in the mine air and the mine water. The clear variation correlates to the change in the underground water flow due to a thaw on the mountain. To eliminate the radon background, the detector water was re-circulated in the closed system of the water purification and the detector tank, since the half life of ^{222}Rn is short (3.8 days).

As discussed in Figure 14, one finds that the trigger rate decreases rapidly after starting water recirculation with the same decay time as that of ^{222}Rn. The trigger rate in 1986 and 1987 is plotted in Figure 20. One notices big spikes of the trigger rate. These spikes resulted from troubles in the water-purification system, mostly water leaks from the apparatus. As a consequence, fresh water had to be supplied, resulting in a sudden jump in the trigger rate.

The next improvement was to make isolation structures from the mine air both in the 3000-ton tank and in the water-purification system. An air-tight ceiling structure on the top surface of the detector tank was constructed in March, 1987. This was just after the detection of SN1987A, which will be discussed in the next section. The sealing

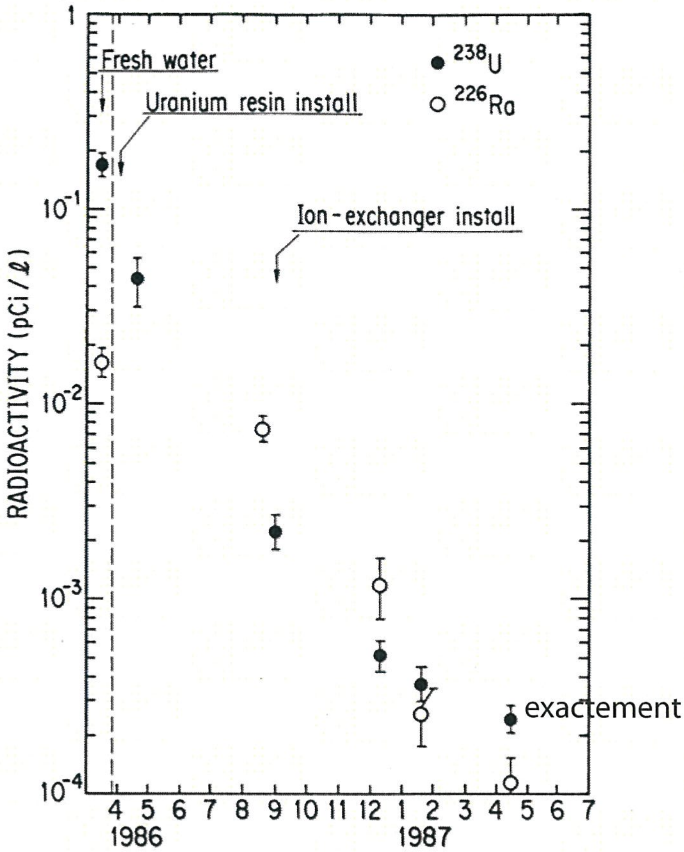

Fig. 18. Reduction of the radioactivity (^{238}U and ^{226}Ra) in the detector water in 1986 and 1987.

of two buffer tanks was completed in May, 1987. Clear decrease in the trigger rate was observed as shown in Figure 20 after finishing the air-tightness operation (May 1987). However, constructing a perfect air-tight ceiling was difficult for these large and complicated structures. Therefore, ^{222}Rn-free air, which was made from the mine air flowing through dry charcoal filters with an efficiency of 99%, was constantly supplied into the top air-tight ceiling of the detector and buffer tanks of the water system.

In 1987, a vacuum degasification system, which was mainly used to remove ^{222}Rn from the water, was installed in the line of the water-purification system. The system was efficient to remove oxygen dissolved in the water as well. After starting the operation of the degasser, unexpectedly the bacteria growth disappeared resulted in the stable water condition.

8 Detection of neutrinos from Supernova SN1987A

Troubles in the water-purification system continued during 1986. Consequently, a jump-up of the trigger rate occurred frequently, as shown in Figure 20. These problems were fixed by the beginning of 1987. The trigger rate has calmed down since then. Supernova SN1987A exploded during the period of a somewhat stable detector condition. The possibility of detecting neutrinos with Kamiokande from a Supernova explosion was mentioned in the proposal [12].

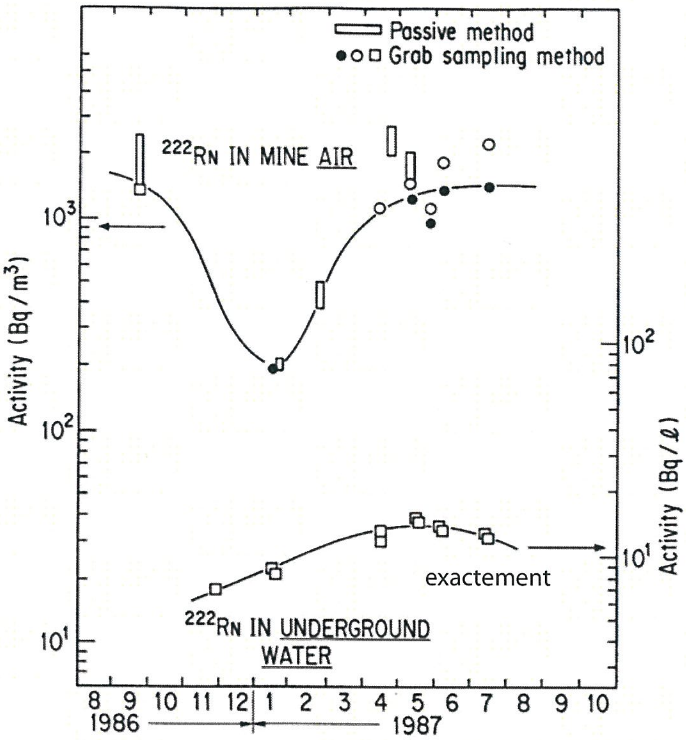

Fig. 19. Annual variation in the ^{222}Rn concentration in the mine air and the mine water.

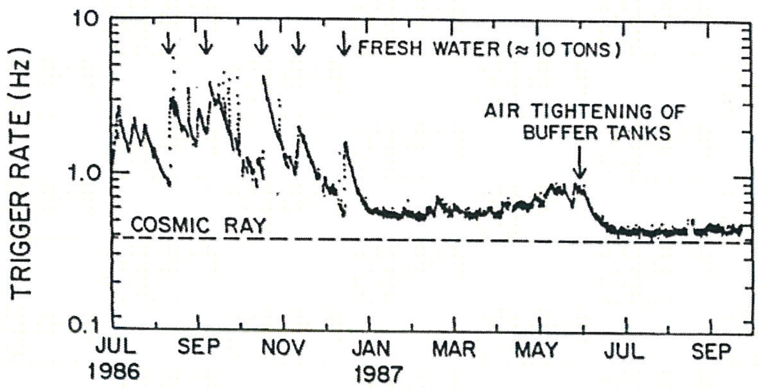

Fig. 20. Trigger rate as a function of time in the early stage of the Kamiokande-II experiment. The trigger threshold was 7.6 MeV. The horizontal broken line shows the trigger rate due to cosmic ray muons (0.37 Hz).

On February 25, 1987, a Fax from the US informed us of the appearance of a supernova in the Large Magellanic Cloud. News of this supernova was quickly sent to the shift persons at the Kamioka mine, and the data tapes until February 25 were immediately sent to Tokyo using a ground transportation service. Since the mine was closed on February 22 and 23, data were continuously taken during these days. It was lucky for the experiment, because from the end of February, it was planned to construct a steel roof on the top of the detector tank in order to protect from the radon in the mine air dissolving into the detector water. However, the company

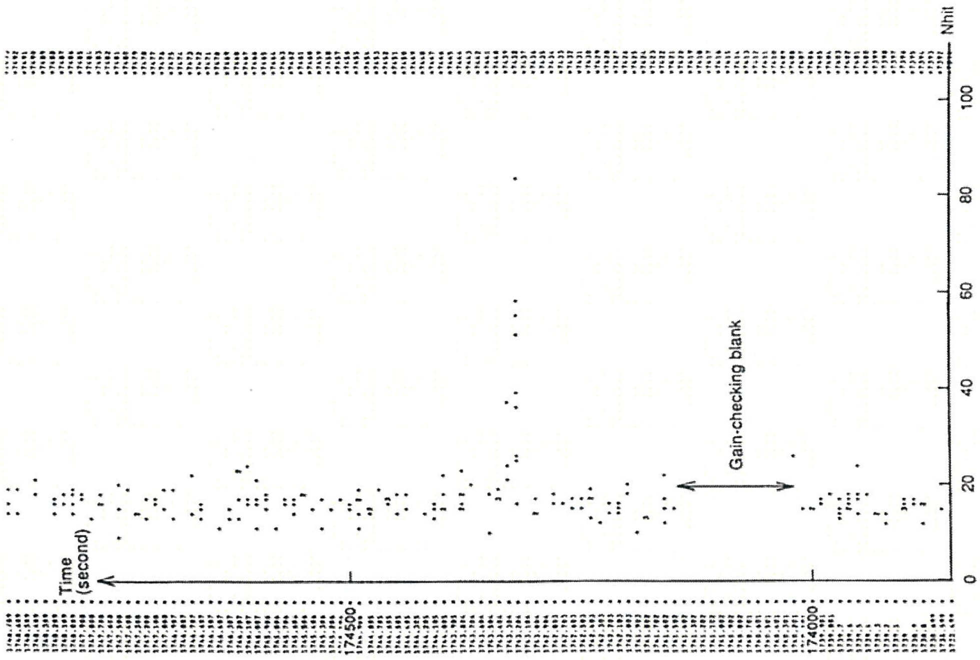

Fig. 21. Computer output of the search for supernova neutrino burst. The number of hit PMTs is plotted as a function of time. A cluster of higher energy events are visible in the middle of the plot. The supernova neutrino burst came 2 min after a data-taking blind period due to an electronics gain check.

postponed this job due to difficulty of arranging workers. The company's judgment regarding this delay was quite fortunate and offered a historical observation.

On February 26, in order to search for the SN neutrino event, it was decided to look for events satisfying the following three criteria: (1) the total number of photo-electrons recorded by the inner detector should be less than 170, approximately corresponding to a 50 MeV electron; (2) the total number of photo-electrons recorded by the outer anti-counter should be less than 30, ensuring event containment; and (3) the time interval from the preceding event should be longer than 20 μs, excluding electrons from muon decays. The data reduction and the vertex-position reconstruction started immediately and this continued on a 24 h basis. The data tapes arrived at Tokyo on February 27. The data between 16:09 February 21 and 07:31 February 24 in Japanese Standard Time were analyzed. It is important to note that the analysis programs for low-energy events had been already ready for the solar-neutrino search. A two-dimensional plot of N_{HIT} (the number of hit PMTs, which was proportional to the energy; $N_{\mathrm{HIT}} = 2.63E$ (MeV)) vs. the event time was made for the entire period. After scanning a few hundred pages of its print-out, a burst of events was immediately found. The burst was discovered on Feb. 28.

Figure 21 shows this scatter-plot. The burst occurred at 16:35:35 23 February, 1987, JST, or at 7:35:35,23 February, 1987, UT ($\pm$1 min) during a time interval of 13 s. The signal consisted of 11 electron events of energy 7.5 to 36 MeV. The paper on this observation was ready by March 6. On March 7, after having sent the paper to post office, a mistake in the calculation of both the right ascension and declination was found. We asked the post office to keep the envelope aside until sending a new one. First of all, we worried that the major part of the paper had to be rewritten. However, double mistakes mostly made the mistake cancel out. The numerical modification

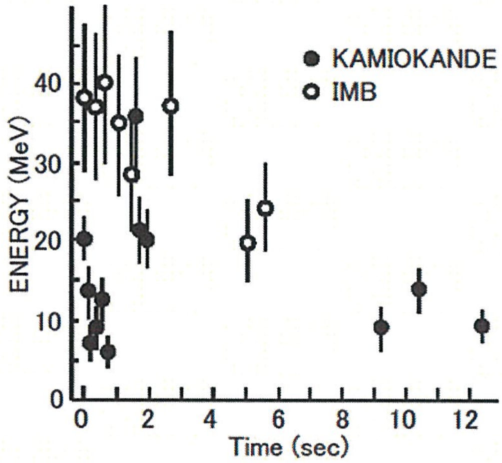

Fig. 22. Comparison of the Kamiokande-II [20] and IMB-3 [22] signals on neutrinos from SN1987A. The time for the first events in both detectors is set to be 0 (s).

gave only a slight change in the table and figures, but no change in the manuscript. A rewritten paper was resubmitted on March 9 (Monday) [20]. A press release was given on the same day. The story concerning how things happened in the Kamiokande collaboration was written in [21] in detail.

The immediate confirmation of the Kamiokande-Il neutrino signal by the 1MB-3 experiment [22] strengthened the credibility of the two observations greatly. Figure 22 compares the signals from Kamiokande-II and IMB-3. There was 6 s time difference in the burst observation between Kamiokande-II (7:35:35 ±1 min, UT) and IMB-3 (7:35:41 ±50 ms, UT). This was due to a large uncertainty of the absolute timing at Kamiokande-II. Kamiokande-II experienced a short power outrage in the mine on February 26. Kamiokande therefore lost a chance to recalibrate its computer clock. The error estimate of ±1 min was based on a check of the data-taking condition on February 21 through a computer terminal from Tokyo.

9 Observation of solar neutrinos

Kamiokande-II studied low-energy electrons produced by the neutrino-electron scattering $\nu + e^- \rightarrow \nu + e^-$. The detection of neutrinos emitted in the reaction $^8B \rightarrow {}^8Be + e^+ + \nu_e$. occurring deep in the Sun was the principal motivation for this study. These neutrinos are called ^{8}B solar neutrinos, and have a continuous energy spectrum up to 14 MeV. This was the first experiment to confirm the results of the radiochemical ^{37}Cl solar neutrino experiment by R. Davis, Jr. and his collaborators [16]. In Kamiokande-II the initial position and the momentum of the recoiling electron were measured. The directionality of the electron detection is a consequence of the kinematics for neutrino-electron scattering ($\theta_e^2 \leqq 2M_e/E_e$), independent of E_ν for $E_\nu \gg M_e$, where, θ_e, E_e, and M_e are the angle, energy, and mass of the electron, respectively. E_ν is the neutrino energy. For 10 MeV electrons, θ_e must be less than about 2 degrees. The detector had an angular resolution of 28 degrees at 10 MeV, and was mainly limited by multiple scattering of electrons in water. This made it possible to point the incident neutrinos back to the Sun. In addition, the observed electron energy spectrum gives information on the energy spectrum of the incident ν. These provide confident evidence for ^{8}B solar neutrinos which comes from the fusion processes occurring inside the Sun.

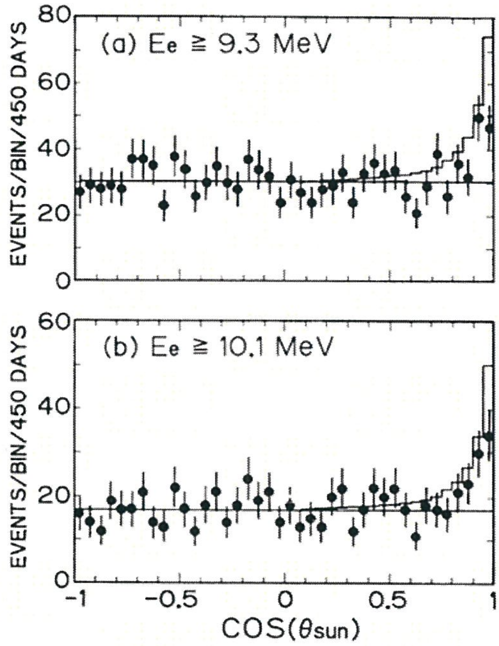

Fig. 23. Angular distributions of events relative to the direction from the Sun, where $\cos(\theta_{sun})$ is the cosine of the angle between the trajectory of an electron and the direction from the Sun at the time of an event. 450 days of the Kamiokande-II data with (a) 9.3 MeV and (b) 10.1 MeV are plotted [25].

The detector performance of Kamiokande-II was first presented at the 7th Workshop on Grand Unification/ICOBAN'86 [23]. The first result concerning the search for solar ^{8}B neutrinos was reported at the 12th Int. Conf. on Neutrino Physics and Astrophysics, Neutrino '86, based on 48.5 days of data [24]. The finite-flux value of solar ^{8}B neutrinos was reported in 1989 [25] (see Fig. 23), and subsequently updated in 1990 [26]. The ^{8}B neutrino flux observed in the Kamiokande-II 450-day data [25] was $0.46 \pm 0.13(\text{stat}) \pm 0.08(\text{syst})$ of the value predicted by the Standard Solar Model [27]. Thus, Kamiokande-II confirmed the neutrino flux from the Sun and reconfirmed the solar neutrino deficit which had been observed in the ^{37}Cl experiment for almost 20 years [28].

The threshold energy for the analysis of solar neutrinos in the initial publication was 9.3 MeV [25]. Thanks to a continuous effort of upgrading the detector, the threshold energies of the trigger and the analysis for the solar neutrino events gradually decreased down to 5 MeV and 7 MeV, as shown in Figure 24. In June, 1988, the detector performance was improved by increasing the gain of the PMTs by a factor of two; thereby improving the discriminator hit efficiency and the PMT timing resolution. As a consequence, the detector performance for solar neutrinos was improved: The increase in the number of hit PMTs in an event led to an improvement in the vertex reconstruction, resulting in a reduction of poorly reconstructed background events in the fiducial volume, and to an improvement in the energy resolution suppressing the low-energy background due to radioactivity.

A major breakthrough in the understanding of the solar neutrino problem was the discovery of the matter effect on neutrino oscillation that converts the neutrino flavor resonantly in the Sun (MSW mechanism) [29–31]. Neutrino oscillations in the vacuum [32,33] and those in the matter [29–31] could be substantially different. Analyses

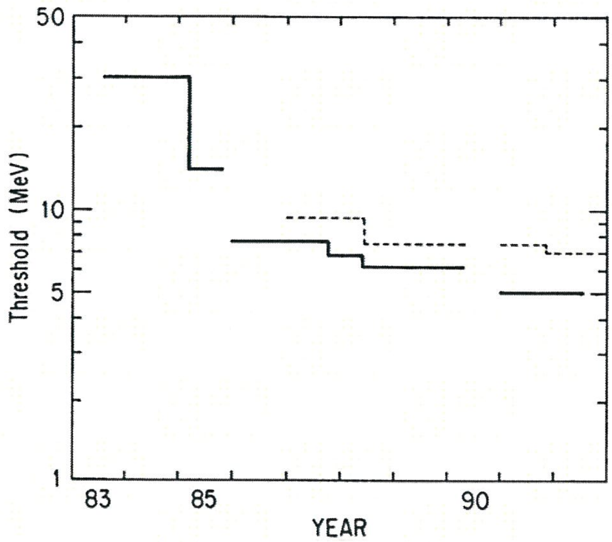

Fig. 24. Thresholds of the detector trigger (solid lines) and the solar neutrino analysis (dashed lines) as a function of time.

of the Kamiokande-II data in terms of the MSW mechanism inside the Sun and the matter effect in the Earth were reported in [34, 35], using 1040 days of data. Both results provided constraints on the neutrino-oscillation parameters.

Although Kamiokande clearly confirmed the solar neutrinos by the directional and energy measurements of these events, the detector was too small to study details of these neutrinos. Experimental data with high enough statistics were waited for.

10 Atmospheric neutrino studies

Atmospheric neutrinos are generated by cosmic ray interactions in the atmosphere. These neutrinos were detected in Kamiokande from the beginning of the experiment. Neutrino oscillation studies with atmospheric neutrinos were considered as one of the items to be studied by Kamiokande as described in the initial proposal [12]. However, in the initial phase of Kamiokande, systematic studies of atmospheric neutrino oscillations were not carried out partly due to the limited manpower available. The detector improvements in Kamiokande during 1985 to 1987 were primarily motivated for the solar neutrino studies. However, these improvements also motivated the systematic improvements of the reconstruction programs for the contained events in the GeV energy range; proton decays and atmospheric neutrino interactions. The improvements included the vertex position reconstruction, the particle identification (showering and non-showering particle separation) and the muon-decay detection. For example, in the initial phase of Kamiokande, the vertex position of an event was reconstructed using the pulse-height (ring-image) information observed by the PMTs. There was a large uncertainty in the vertex position perpendicular to the particle direction. In Kamiokande-II, the vertex position was reconstructed primary by the timing information of each PMT, and therefore the resolution in the vertex position was improved substantially.

Typically, in the high-energy cosmic-ray interactions with the air nuclei, many π mesons, and less abundantly K mesons, are produced. Since these mesons are unstable, they decay to other particles. For example, a π^+ decays to a muon (μ^+) and a ν_μ. The produced muon (μ^+) is also unstable and decays to a positron (e^+), a $\bar{\nu}_\mu$ and a ν_e. Similar decay processes occur for π^- and K mesons.

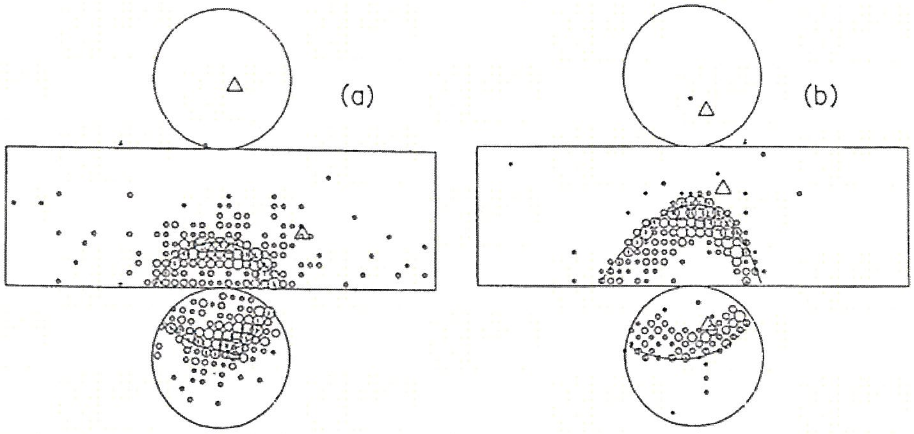

Fig. 25. Event pattern for (a) an e-like and (b) a μ-like event observed in Kamiokande. Each circle represents a PMT which detected Cherenkov photons; the area of the circle is proportional to the observed photo-electron number.

One important piece of information for the study of neutrinos is the type of particles produced. An electron produced in the detector by a ν_e interaction propagates in the water producing an electro-magnetic shower. The ring image of the Cherenkov radiation due initially to an electron is the summation of the ring images of many electrons and positrons in the electro-magnetic shower and shows a fuzzy ring pattern. On the other hand, a muon produced by a ν_μ interaction propagates in the water almost straightly loosing the energy slowly without producing an electro-magnetic shower. Consequently the ring image due to a muon shows a clearer ring pattern. Therefore, it is possible to separate Cherenkov rings due to an electron (e-like or showering type) and a muon (μ-like or non-showering type).

The ability to separate Cherenkov rings due to electrons and muons depends on the amount of information one can get from the ring image, and therefore depends on the amount of Cherenkov photons one can observe. In this sense, Kamiokande was suited to carry out this analysis due to the use of the large PMTs. In fact, it was stressed by M. Koshiba already in the preparation stage of the experiment that it was very important to separate non-showering and showering particle types with the information available with the large number of PMTs that detected Cherenkov photons. The number of photoelectrons for 1 GeV/c electrons and muons was about 3000, which was large enough for the efficient identification of e-like and μ-like Cherenkov rings. This feature was fully utilized only when a dedicated program to separate electron and muon Cherenkov rings was developed in 1986. The particle identification program utilized the maximum likelihood method. The observed event pattern of a Cherenkov ring was compared with the expectations assuming either an electron or a muon for the reconstructed vertex position, particle direction and the total number of photo-electrons. The Cherenkov rings were separated to "e-like" and "μ-like". Figure 25 shows an e-like and a μ-like event observed in Kamiokande. The estimated probability of correctly identify the types was 98%.

In late 1986, a hint of a deficit of μ-like events relative to the Monte Carlo prediction of atmospheric neutrino interactions was observed in Kamiokande. One possibility recognized immediately was a deficit of the ν_μ flux by some unknown physical processes, since more than 90% of μ-like events were predicted to be due to ν_μ interactions. However, it was possible that some unrecognized problem with the detector or the data analysis was the cause of the deficit. Therefore, various studies on the deficit of μ-like events started immediately after the initial recognition of the deficit. It took almost a year to complete the studies. These studies, however, did not find any problem.

In 1988, Kamiokande reported a result on the studies of atmospheric neutrino events [36]. The number of e-like events of the data, 93 ± 9.6(stat) agreed with the Monte Carlo prediction (88.5) within the statistical error of the data. However, the observed number of μ-like events, 85 ± 9.2(stat) was much smaller than the predicted number of events (144.0). The ν_μ/ν_e ratio of the flux was accurately predicted, although the predicted absolute neutrino flux at that time had more than 20% uncertainty. Therefore, it was clear that the comparison between the data and the Monte Carlo prediction should be made by taking the (μ-like/e-like) ratio. The discrepancy in the (μ-like/e-like) ratio between the data and the prediction could have been due to a new physics effect neglected in the Monte Carlo simulation. One possibility that was mentioned in the paper was neutrino oscillations. If ν_μ oscillated to ν_τ with a large mixing angle, it was possible to explain the deficit of the ν_μ events.

Soon thereafter it was pointed out [37] that the flux calculation adopted in the Kamiokande analysis did not take into account the effect of polarization of cosmic ray muons in their decay. Muons from pion decay are completely polarized in the pion rest frame. Since neglecting the muon polarization underestimates the energy of electron-neutrinos and anti-electron-neutrinos, the polarization effect might account for the small μ-like/e-like ratio of the data. Following this suggestion, the effect of the muon polarization on the atmospheric neutrino flux was estimated [38]. It turned out that the change in the ν_μ/ν_e flux ratio due to the effect of the polarization was less than 15% in the GeV energy range. This was not large enough to account for the observed muon deficit fully. The updated results from Kamiokande with the muon polarization effect were reported (see for example [39]). The essential conclusion did not change with the polarization effect in the flux.

Subsequently, Kamiokande published the second paper in 1992 on this topic with the increased data statistics and including the results on the neutrino oscillation analysis [40]. Neutrino oscillation was predicted in the 1960's [32, 33]. In the analysis, data were compared with Monte Carlo predictions with several flux models [41–43]. It was found that [(μ-like/e-like)$_\mathrm{data}$/(μ-like/e-like)$_\mathrm{MC}$] was essentially independent of the choice of the flux model. Both $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_\mathrm{e}$ were tested and concluded to be allowed, because the small μ-like/e-like ratio can occur for both oscillation cannels, independent of the absolute neutrino flux, which had an uncertainty of 20% or larger. It should be noted that the existence of several groups that calculated the atmospheric neutrino flux independently was very importance to get convincing results. At that time, it was already recognized that the solar neutrino problem could be due to $\nu_\mathrm{e} \to \nu_\mathrm{x}$, where ν_x was ν_μ and/or ν_τ (MSW mechanism). Therefore it was concluded that $\nu_\mu \to \nu_\tau$ oscillations might account for the observations based on combined information of atmospheric and solar neutrino data.

The observation of the deficit of μ-like events was very interesting, suggesting neutrino oscillation as a possibility. However, at that stage, neutrino oscillation was only one of the possibilities. It was thought that other evidence that strengthen the published results and gave independent information in identifying the underlying physics was required.

If the ν_μ deficit observed in the data sample, whose mean energy was in the sub-GeV energy range was due to neutrino oscillations, the deficit should also be observed in the higher energy range, since there is a well known relation [32, 33] between the neutrino oscillation probability and the neutrino energy;

$$P\left(\nu_\mu \to \nu_\mu\right) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2\left(\mathrm{eV}^2\right) L_\nu(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right),$$

where $P(\nu_\mu \to \nu_\mu)$ is the probability that a ν_μ remains as ν_μ, θ is the neutrino mixing angle, Δm^2 is the difference of the neutrino mass squared, L_ν is the neutrino flight length and E_ν is the neutrino energy.

Furthermore and more importantly, if the observed ν_μ deficit was due to neutrino oscillations, the deficit should depend on the neutrino flight length, and therefore depend on the zenith angle. However, in the sub-GeV energy range, the correlation between the neutrino direction and muon direction is rather poor. The zenith angle dependence in the neutrino direction is largely washed out in the muon zenith-angle distribution in this energy range. The angular correlation between neutrinos and charged leptons becomes better substantially with increasing neutrino energy, and the zenith angle distribution for muons should represent the neutrino zenith angle distribution fairly well for multi-GeV neutrino events. If the neutrino oscillation length is about 1000 km for the neutrinos considered here, one expects that the ν_μ deficit should be observed in the upward-going directions, since the neutrino flight length is much less than 1000 km and much more than 1000 km for downward-going and upward-going neutrinos, respectively. This was thought to be an important measurement, since only neutrino oscillations can generate such up-down asymmetry.

Therefore, within one month after submitting the first paper on the atmospheric ν_μ deficit in 1988, Kamiokande started to select atmospheric ν_μ events with the multi-GeV energy range from the raw data stored since 1983. In the earlier atmospheric neutrino analysis, fully-contained events were selected as a byproduct of the proton decay searches. Hence the energy range covered was less than 1.3 GeV. A multi-GeV ν_μ interaction typically produces a multi-GeV muon. These multi-GeV muons produced in the detector typically penetrate through the inner detector, reaching to the veto-counter and eventually to the surrounding rock. Neutrino interactions occurring inside the inner detector, accompanied with a muon that penetrates through the inner detector, can be identified by a signal in the veto-counter. These events are called partially-contained (PC) events. Since muons are essentially the only charged particle that can propagate the water for more than a few meters, most of the partially-contained events are ν_μ interactions.

Since the flux of the atmospheric neutrinos decreases rapidly as the energy increases, the event rate for the multi-GeV ν_μ events was only about 20 per year in Kamiokande. It took several more years to collect statistically meaningful number of such events. Finally, in 1994, Kamiokande reported the multi-GeV atmospheric neutrino data [44]. The μ-like data showed deficit of events in the upward-going direction, while the downward-going μ-like events did not show such deficit. Furthermore, the corresponding distribution for e-like evens did not show any evidence for the deficit of upward-going events. Figure 26 shows the observed zenith angle distributions for multi-GeV neutrino events in Kamiokande. The statistical significance of the observed up-down asymmetry in the μ-like events was 2.8 standard deviations. If a double-ratio $[(\mu\text{-like/e-like})_{\text{data}}/(\mu\text{-like/e-like})_{\text{MC}}]$ is plotted as a function of the zenith angle, one can see that the double-ratio shows the dependence as shown in the right panel of Figure 26. It was an interesting observation, which showed, for the first time, that the ν_μ deficit depended on the neutrino flight length as predicted by neutrino oscillations. However, the statistical significance was not strong enough to be conclusive. Experimental data with high enough statistics were waited for.

As described so far, we believe that the Kamiokande experiment contributed substantially to the birth of the neutrino astrophysics and neutrino oscillation physics. However, some of the issues remained unresolved. Next generation experiments were required to resolve some of the questions. Hereafter, we briefly describe the second and the third generation neutrino experiments at Kamioka.

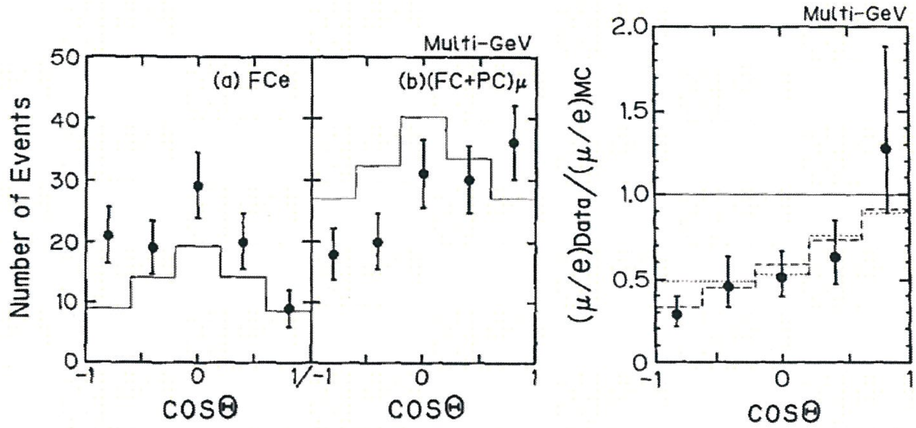

Fig. 26. Left panel: Zenith angle distributions for multi-GeV neutrino events in Kamiokande [44]. In panel (b), fully-contained, multi-GeV, single-ring μ-like events and partially-contained μ-like events are combined together. Right panel: Zenith-angle distribution of $[(\mu\text{-like/e-like})_{\text{data}}/(\mu\text{-like/e-like})_{\text{MC}}]$. The circles with error bars show the data. Expectations from the MC simulation with oscillation are also shown by dotted ($\nu_\mu - \nu_\tau$) and dashed ($\nu_\mu - \nu_e$) histograms.

11 Super-Kamiokande

Large-volume underground detectors before the 1990's have opened new research fields in elementary particle physics and astroparticle physics. As a future major experiment at Kamioka, a large water Cherenkov detector with a sensitive mass of 32 000 ton was proposed in 1983 and presented, for the first time, at the Workshop on Grand Unified Theories and Cosmology, which was held in KEK [45]. The name of the experiment was initially called JACK (Japan-America Collaboration at Kamioka). The original idea came from M. Koshiba. In the autumn of 1983, when the ^{8}B solar neutrino studies with Kamiokande was proposed, M. Koshiba thought that the event rate was too low for Kamiokande to carry out detailed studies of solar neutrinos as an observatory. Therefore, in order to really open a new field of neutrino astrophysics, a detector with a much higher event rate, and therefore a much larger detector than Kamiokande, was required. This was the motivation for M. Koshiba to propose this detector. The name of Super-Kamiokande was given to this detector in the following year (1984) [13,46]. Super-Kamiokande was also presented for the first time, to wider audience at the 22nd Int. Conf. on High Energy Physics [13]. The detector performance of Super-Kamiokande was presented in detail at the 7th Workshop on Grand Unification/JCOBAN '86 [47].

As the experimental site, the Kamioka mine was still the best candidate, due to the good rock condition and many available mine services; electric power, rock maintenance, transportation and so on. However, it was the first experience in Japan to excavate such a large cavity (approximately 10^5 m^3) with a dome shape deep underground. Different kinds of tests were carried out in order to investigate the rock mechanical characteristics by the Kamioka mine company, and also by a project team of civil-engineering companies and universities during 1986 to 1990. The most suitable site for Super-Kamiokande was decided, based not only on the obtained test results of the rock condition, but also on a consideration of the rock overburden, which should be as least as deep as the depth of Kamiokande. Figure 27 shows the positions of Kamiokande and Super-Kamiokande on a topographical map. The Super-Kamiokande site is about 200 m south-west from the Kamiokande site.

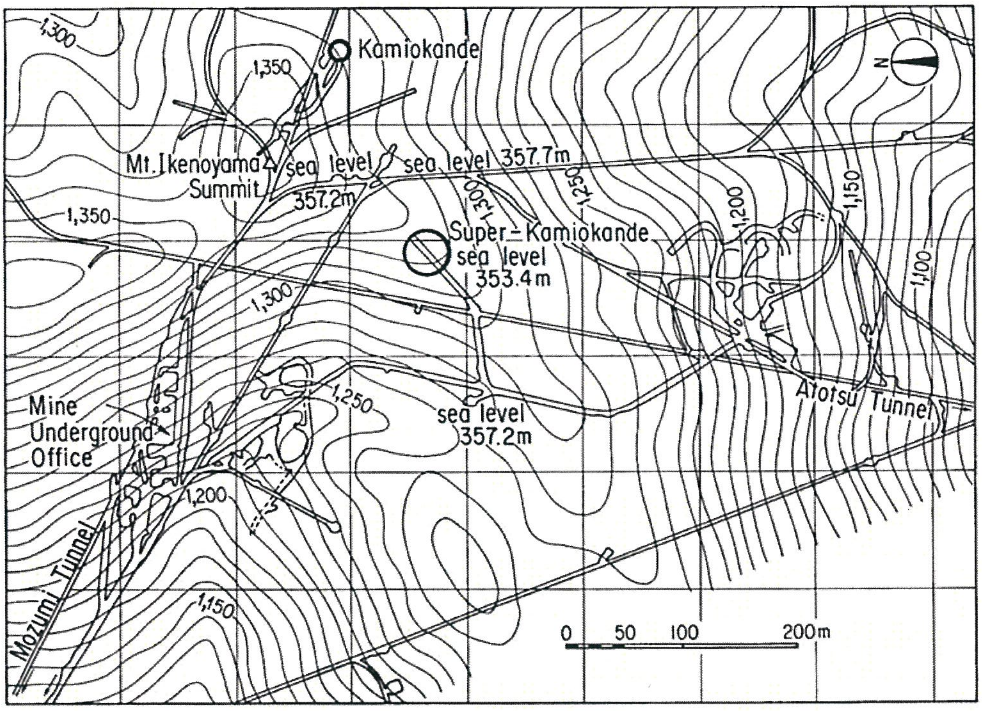

Fig. 27. Positions of Kamiokande and Super-Kamiokande in the Ikenoyama mountain.

The final design of the Super-Kamiokande detector was determined to have a 50 000 m^3 cylindrical tank; 42 m high and 39 m diameter. The side and bottom walls of the cavity were laid by thin stainless steel. The thin stainless steel wall was able to hold the 50 000 ton water inside the container, because the stainless steel walls were attached to the outer concrete layer and eventually to the surrounding rock. 11 200 20-inch PMTs were placed uniformly over the entire inner surface, giving a 40% photo-cathode coverage, which was 2-times larger than that of Kamiokande. The support structure of the 20-inch PMTs was positioned at about 2 m inside from the tank walls (top, side and bottom). The total mass of water inside the PMT surface was 32 500 ton. The outer volume of the detector was used as a veto-counter layer. Black-and-white polyethylene sheets were lined just behind the inner 20-inch PMTs and optically separated the inner and outer volumes. The 22 500-ton fiducial mass was approximately 22-times larger for proton-decay detection and 32-times lager for solar-neutrino detection, than those of Kamiokande. Figure 28 shows the Super-Kamiokande detector. Table 1 compares the detector parameters of Kamiokande and Super-Kamiokande. More details of the Super-Kamiokande detector can be found in [48].

The Super-Kamiokande project was officially approved by the Japanese government in 1991. Various supports, including those by scientists in Japan and abroad, have been one of the reasons for the approval. In addition, the successful detection of Supernova and solar neutrinos motivated the government's approval. The excavation for the detector cavity started in the same year. In 1992, the US group, formed mostly by the previously IMB group, visited Y. Totsuka, the spokesperson of Super-Kamiokande, for the possible collaboration within Super-Kamiokande. The US group proposed to construct the outer detector, whose main function is to identify the incoming and outgoing relativistic charged particles. This proposal was approved by the

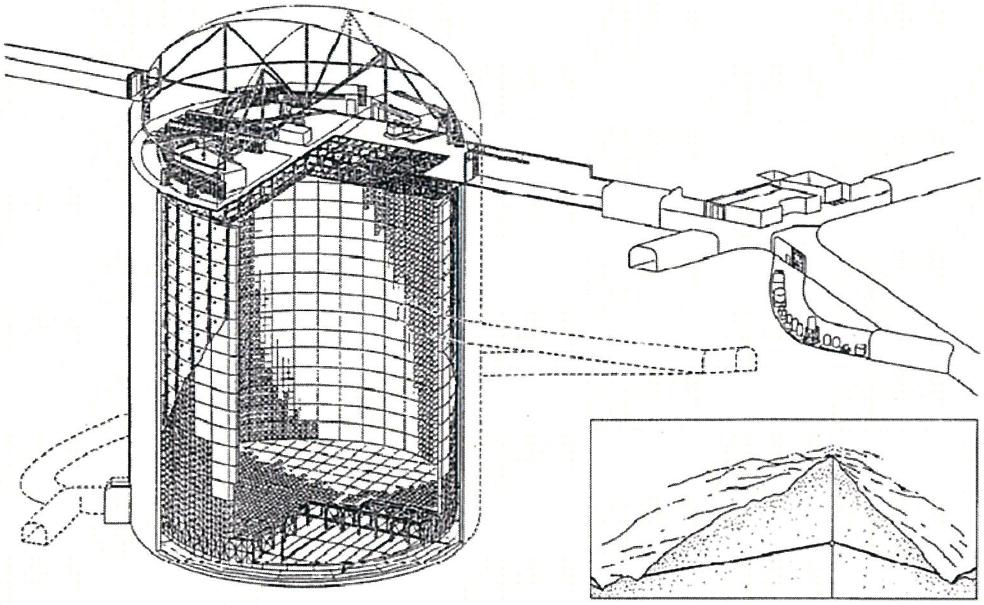

Fig. 28. The Super-Kamiokande detector. The detector tank is 42 m high and 39 m diameter.

Table 1. Parameters of Kamiokande and Super-Kamiokande.

Parameters	Kamiokande-II	Super-Kamiokande	Remarks
Dimension	16 mh × 19 mϕ	42 mh × 39 mϕ	
Total mass	4 500 t	50 000 t	
Fiducial mass	680 t 1040 t 2140 t	22 500 t 22 500 t 32 500 t	solar ν proton-decay/ atmospheric ν supernova ν
Number of PMTs (inner detector)	948	11 200	
Photo-cathode coverage	20%	40%	
Energy resolution	$3.6\%/\sqrt{E\,(\mathrm{GeV})}$ 4%	$2.5\%/\sqrt{E\,(\mathrm{GeV})} + 0.5\%$ 3%	e (GeV range) μ
Energy threshold for solar neutrino analysis	7.5 MeV	5.0 MeV	
Particle ID (e/μ separation)	98%	99%	

Japanese group, thus forming the Super-Kamiokande international collaboration. The collaboration agreement between Japanese and US members was signed on Oct. 18, 1992. The proposal by the US group to participate in Super-Kamiokande was written in Dec. 1992 [49], and submitted to the US Department of Energy.

The detector construction took 5 years. The data taking started on 1 April, 1996 as originally scheduled. The preparation, construction and the operation of the Super-Kamiokande detector was led by Y. Totsuka until 2002. Super-Kamiokande has been contributing substantially to neutrino physics and astrophysics through the detection of solar and atmospheric neutrino events.

Super-Kamiokande was able to produce reliable results on atmospheric neutrinos in a relatively short time after the start of the experiment due to the readiness of

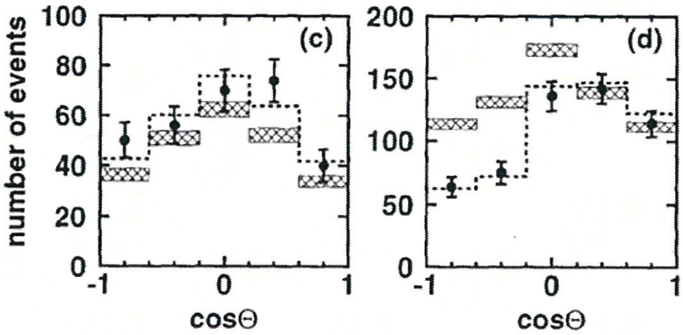

Fig. 29. The zenith angle distributions shown in Neutrino'98 [51]. The left panel shows the zenith angle distribution for multi-GeV (namely, the visible energy of an event must be larger than 1.33 GeV) e-like events, while the right panel shows that for fully-contained multi-GeV μ-like plus partially-contained neutrino events.

the analysis and Monte Carlo programs. However, it was realized that the analysis program must be fully automated in order to fully utilize such high statistics data. It took more than a year to prepare the fully automatic analysis. The analysis results based on the automatic analysis began to be shown outside of the collaboration in the summer of 1997 [50]. By the spring of 1998, Super-Kamiokande analyzed 535 days of data, or equivalently 33 kilo-ton $\times$ year detector exposure. The total number of atmospheric neutrino events was 5 400, which was about 4 times more statistics than those in Kamiokande.

At the 18th International Conference on Neutrino Physics and Astrophysics (Neutrino'98), Super-Kamiokande made an announcement of the evidence for atmospheric neutrino oscillations [51, 52]. The evidence for neutrino oscillations was obtained by several different measurements. The ν_μ/ν_e flux ratio was measured with greater precision, showing significantly smaller ratios than the prediction in both the sub- and multi-GeV energy ranges. The strongest evidence for oscillation came from the zenith angle distributions. The zenith angle distributions shown in Neutrino'98 are shown in Figure 29. The left panel of Figure 29 shows the zenith angle distribution for multi-GeV (namely, the visible energy of an event must be larger than 1.33 GeV) e-like events, while the right panel shows that for fully-contained multi-GeV μ-like plus partially-contained neutrino events. It was clear that the deficit of upward-going events was observed in the μ-like data sample. The statistical significance was more than 6 standard deviations, implying that the deficit was not due to a statistical fluctuation. On the other hand, the zenith angle distribution for e-like events did not show any statistically significant up-down asymmetry. Furthermore, the zenith-angle distribution for upward going muons, which are produced by high-energy atmospheric ν_μ interactions in the rock below the detector, did not agree with the no-oscillation prediction. It was concluded, from these data, in particular from the zenith angle distributions shown in Figure 29, that muon-neutrinos oscillate to other types of neutrinos, most likely to tau-neutrinos.

The data were analyzed assuming $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillations. Figure 30 shows the summary of the oscillation analyses from Super-Kamiokande as well as those from Kamiokande in 1998 [52]. Contours of allowed neutrino oscillation parameters obtained from Super-Kamiokande and Kamiokande reasonably overlapped, indicating that the data were consistently explained by neutrino oscillations. The "atmospheric neutrino anomaly" was concluded to be due to neutrino oscillations.

The discovery in 1998 was due to muon-neutrino disappearance. Therefore, there remained a question whether the oscillations are $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_{\mathrm{sterile}}$, where ν_{sterile}

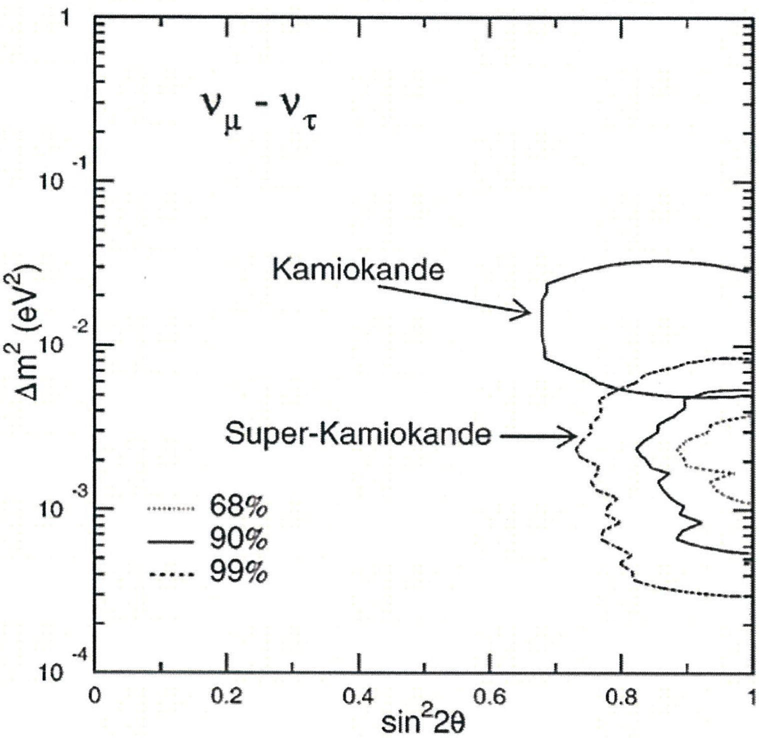

Fig. 30. Summary of the oscillation analyses from Super-Kamiokande as well as those from Kamiokande in 1998 [52]. $\nu_\mu \to \nu_\tau$ oscillations were assumed.

are "sterile neutrinos", which do not interact with the ordinary matter. In 2000, Super-Kamiokande concluded that $\nu_\mu \to \nu_\tau$ was favored over $\nu_\mu \to \nu_{\text{sterile}}$ by detailed analyses of upward-going muons, partially-contained events and neutral-current enriched events [53]. Furthermore, in 2006, Super-Kamiokande analyzed the "τ-like" events, and showed that the data favor the appearance of ν_τ generated by neutrino oscillations at the significance of 2.4 standard deviations [54].

Super-Kamiokande detects ^{8}B solar neutrinos through neutrino-electron scattering. The electron energy, direction and time of the reaction are measured. From the beginning of the project, it was realized that a very precise calibration of the energy scale was critical for the science with a high event-rate neutrino observatory. Therefore, Nakahata et al. installed an electron linear accelerator (LINAC) with the maximum energy of 16 MeV to an access tunnel to Super-Kamiokande [55] (see Fig. 31). In addition to the energy scale, energy resolution, angular resolution and the vertex position resolution were calibrated mainly by the electron LINAC system. The absolute energy scale has been understood within 0.64% in this energy range.

The radioactive background sources for solar neutrinos had been studied in Kamiokande. Therefore, in designing the Super-Kamiokande detector, various improvements were made in the water and air purification system and the detector tank itself. As of 1999, the typical Radon concentration in the top and bottom regions of the Super-Kamiokande tank was less than 1.4 mBq/m^3, and 3 to 5 mBq/m^3 [56], respectively, which were about 2 orders of magnitude less than those in Kamiokande.

As the result of these improvements, Super-Kamiokande precisely measured the flux of solar neutrinos. Figure 32 shows the angular distribution of the candidate solar neutrino events obtained during 1496 days of the detector exposure for a

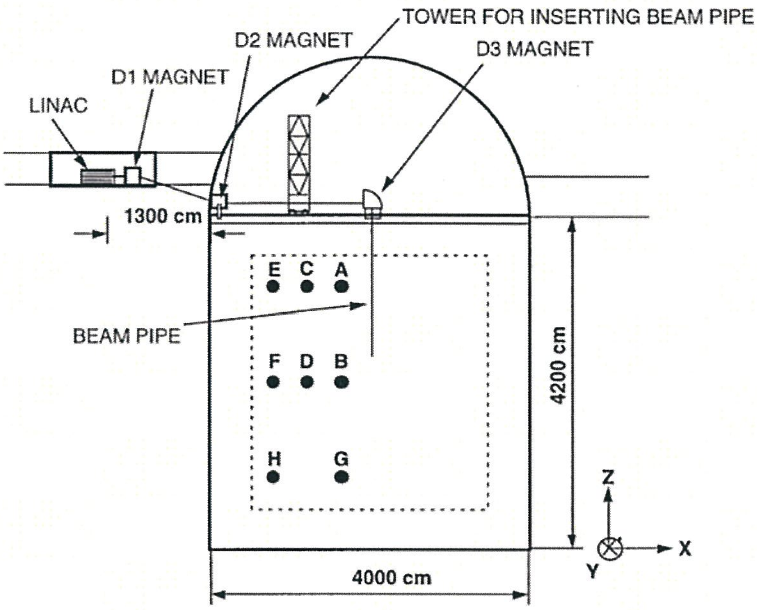

Fig. 31. The LINAC and its beam line for the calibration of the Super-Kamiokande detector. The black dots show the locations where the electrons from LINAC are injected to the Super-Kamiokande detector [55].

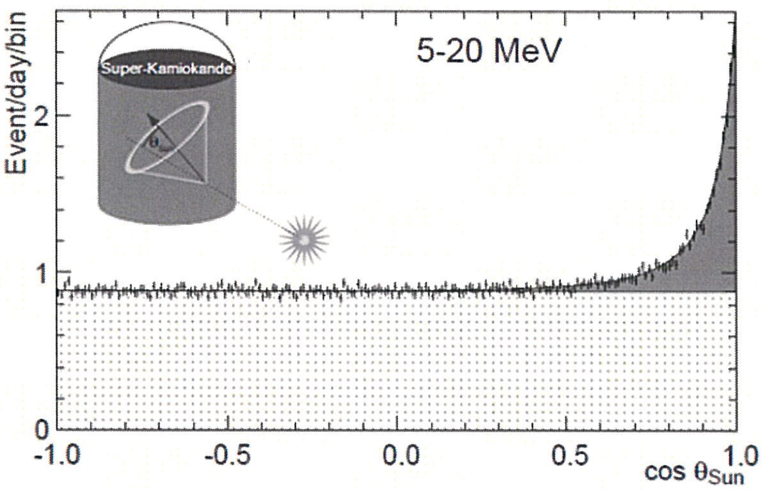

Fig. 32. Angular distribution of the candidate solar neutrino events with the threshold of 5 MeV for the 1496 days of exposure in Super-Kamiokande-I. The shaded area indicates the elastic scattering peak. The dotted area is the contribution from background events.

threshold of 5 MeV [57]. The measured solar neutrino flux from ^{8}B decay was $2.35 \pm 0.02(\text{stat}) \pm 0.08(\text{syst}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$, significantly smaller than the solar model prediction. The measured energy spectrum was consistent with that expected from neutrino-electron scatterings of ^{8}B solar neutrinos

In 2001, an important result was obtained by comparing the results from SNO and Super-Kamiokande. SNO observed ^{8}B solar neutrinos by $\nu_e \mathrm{D} \rightarrow \mathrm{e}^- pp$ charged current (CC) interaction [58]. On the other hand, Super-Kamiokande observes ^{8}B solar

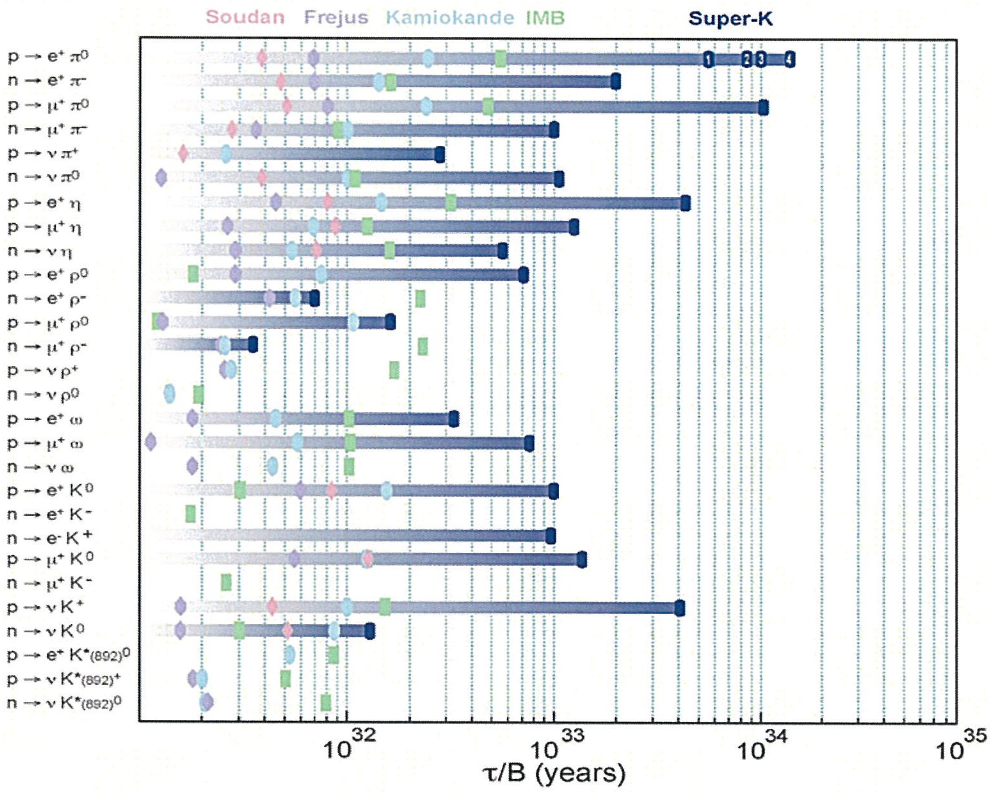

Fig. 33. 90% C.L. lower limits on the lifetime of nucleon for various decay modes. Limits from Super-Kamiokande [61,62], together with those from earlier experiments [63] are shown [60].

neutrinos by the neutrino-electron scattering. The cross section for the ν_e-electron scattering is larger than that for the $\nu_{(\mu\,\mathrm{or}\,\tau)}$-electron scattering by a factor of about 7. Therefore, if neutrinos oscillate, it is expected that the flux observed in Super-Kamiokande is larger than that observed in SNO assuming that all neutrinos are ν_e. The observed flux in SNO by the CC interaction was $1.75 \pm 0.7(\mathrm{stat.}) + 0.12/-0.11(\mathrm{syst.}) \pm 0.05(\mathrm{theor.}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which was 0.347 ± 0.029 (stat.+syst.) of the solar model prediction. The observed flux by SNO was 3.3 standard deviations smaller than that by Super-Kamiokande. This discrepancy gave the first direct evidence for solar neutrino oscillations, because the higher flux observed in the neutrino-electron scattering is interpreted as due to $\nu_{(\mu\,\mathrm{or}\,\tau)}$-electron scattering. (Later in 2002, a more compelling evidence for oscillation was reported by SNO by comparing flux measured by charged current interaction and neutral current interaction, $\nu_e \mathrm{D} \rightarrow \nu_e\, p\, n$, both measured by SNO [59]).

The original motivation for Kamiokande was the search for nucleon decay. Although the original non-Super-Symmetric SU(5) Grand Unified model [2] was excluded by the non-observation of nucleon decays in the experiments in the 1980's, the idea of Grand Unification is still believed to be valid. Therefore, nucleon decays are still searched for in Super-Kamiokande. Although there has been still no evidence for proton or bound neutron decay, the Super-Kamiokande experiment has set stringent limits on nucleon partial lifetime for various decay modes, as summarized in Figure 33. The 90% C.L. limits are 1.3×10^{34} and 4.0×10^{33} years for the decay modes of $p \rightarrow e\,\pi^0$ and $p \rightarrow \nu\,\mathrm{K}^+$, respectively [60–62].

In the summer of 2001, after 5 years of operation of the Super-Kamiokande detector, the detector water was drained to replace dead PMTs. After the PMT replacement work, the detector was refilled with pure water. On Nov. 12, 2001, more than 6000 PMTs located below the water surface, which was about 30 m from the bottom of the detector tank, were destroyed at a time. This accident was due to an implosion of one PMT in the detector water, producing a strong shock wave, destroyed the adjacent PMTs. The destroyed PMTs generated another shock wave, further destroyed the adjacent PMTs. This way, more than 6000 PMTs were destroyed at a time. The next day, Y. Totsuka declared that the detector would be reconstructed on the webpage of the Kamioka Observatory, ICRR. Reading this message, all the collaborators, with all kinds of warm help from the world community, worked toward the reconstruction of the Super-Kamiokande detector. The Super-Kamiokande detector was re-built in 2002 with approximately a half of the original inner detector PMT density (Super-Kamiokande-II). The experiments were resumed in Oct. 2002 with this configuration. While taking data in Super-Kamiokande-II, new PMTs were produced. In June 2006, with the installation of more than 6000 new PMTs, the experiments with the original photo-cathode coverage (Super-Kamiokande-III) were resumed.

The study of neutrino oscillations with atmospheric neutrinos is still continuing. At the same time, Super-Kamiokande has been used as the far-detector in long-baseline neutrino oscillation experiments, in which neutrinos are produced by high-energy proton accelerators.

K2K was the first longbaseline neutrino oscillation experiment. The neutrino beam was produced by a 12 GeV proton synchrotron at KEK. Every 2.2 s, about 6×10^{12} protons were accelerated, extracted from the accelerator and hit the target, producing numerous charged pions. Among these pions, only positive pions were focused by a set of magnetic horns to the direction of Super-Kamiokande. These pions decay into μ^+ and ν_μ in the 200 m long tunnel. The beam of ν_μ thus produced had the mean neutrino energy of about 1.3 GeV. These neutrinos were detected at the near detector complex and at Super-Kamiokande, which was located 250 km away from the target. This experiment was started in 1999 and continued until 2004, and clearly confirmed neutrino oscillation [64].

The subsequent long-baseline experiment using Super-Kamiokande is the T2K experiment. Neutrinos are produced by the J-PARC accelerator complex and detected in the Super-Kamiokande detector. The baseline length is 295 km. The main purposes are the discovery of the oscillation induced by the third mixing angle θ_{13}, and the precise measurement of Δm^2 and $\sin^2 2\theta_{23}$. J-PARC was designed to accelerate 3×10^{14} protons every 3.4 s to 40 to 50 GeV energies. The originally designed beam power was 750 kW. As of spring 2011, the beam power of 145 kW has been achieved with the proton energy of 30 GeV. T2K uses the off-axis technique to tune the neutrino energy to maximize the oscillation effect. Taking the current best-fit value of Δm^2 into account, the off-axis angle was set to be 2.5 degrees, which gave the peak flux at 0.6 GeV. The experiment was started in 2010.

In 2011, the T2K experiment reported indication of electron neutrino appearance and therefore a non-zero θ_{13}, based on data taken between Jan. 2010 and March 2011. T2K observed 6 candidate electron events, while the expected number of background events was 1.5 ± 0.3 [65]. T2K plans to take much more data. It is expected that T2K will improve our knowledge on neutrino masses and mixing angles substantially.

12 KamLAND

Studies of radioactive background and low background technologies in Kamiokande and Super-Kamiokande made it possible for A. Suzuki to propose a new neutrino experiment using low-background liquid scintillator. In the 1990's, the solar neutrino

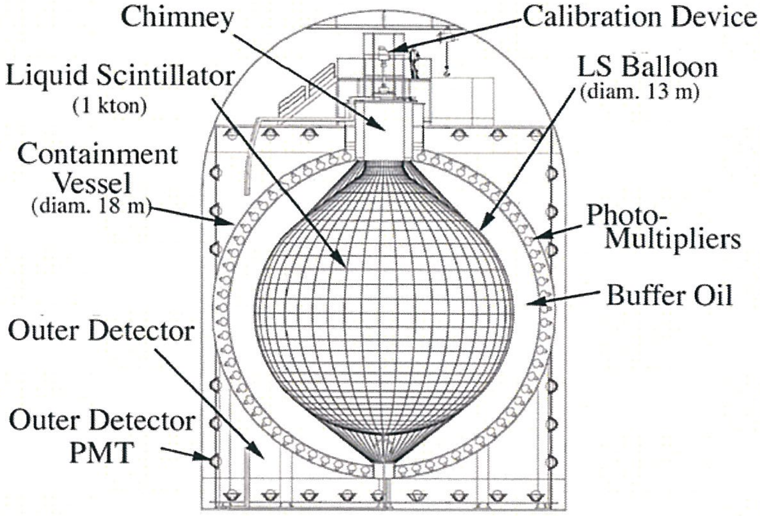

Fig. 34. Schematic view of the KamLAND detector.

problem suggested several allowed regions of neutrino oscillation parameters. One of them was the Large Mixing Angle (LMA) solution. A. Suzuki noticed that the LMA solution can be studied by a long-baseline reactor-neutrino experiment [66, 67]. The typical neutrino mass squared difference (Δm^2) for the LMA solution was (several $\times 10^{-5}$) eV^2, which could be studied by a reactor experiment with the baseline longer than ~100 km.

KamLAND is a monolithic liquid scintillator detector, which contains 1 000 ton of ultra-pure liquid scintillator. Figure 34 shows the KamLAND detector. The detector is located at the old Kamiokande site after dismantling the Kamiokande detector. A nuclear reactor is a very intense source of anti-electron-neutrinos. There are many commercial nuclear power plants around Kamioka as shown in Figure 35. These reactors, distributed at 130–220 km distances from KamLAND, generated 7% of the world total reactor power; 70 giga-watts (GW) over 1.1 trillion watts (TW). This situation provides an effective baseline of about 180 km for the neutrino oscillation study and gives a superior sensitivity to determine the neutrino masses. In 1999, J. Bahcall, who was the leading theorist in the field of solar neutrinos, commented on KamLAND, "I never expected to live to see a laboratory test of a solar neutrino explanation" [68].

In December 2002, KamLAND reported the first result on reactor neutrino disappearance with 99.95% C.L. significance [69]. The improved statistics strengthened the significance of neutrino disappearance in 2005 [70] and 2008 [71] and observed the clear oscillation pattern. Figure 36 shows the most updated data from KamLAND, which shows (data/no-oscillation expectation) as a function of L/E [72]. In the context of two-flavor neutrino oscillations, KamLAND succeeded in pinning down the solution of the solar neutrino problem to the LMA solution. Figure 37 shows the allowed regions of 2-flavor $\nu_e \rightarrow \nu_x$, where ν_x represents ν_μ and ν_τ, oscillation parameters as of 2011 [72]. The oscillation parameters have already been measured accurately. The solar neutrino problem has been solved completely. This, in turn, means that the detailed studies of the solar neutrino flux have just been made possible.

As a bi-product, the KamLAND experiment observed geo-neutrinos for the first time. A basic factor in the interior dynamics of plate tectonics, mantle convection, terrestrial magnetism and the evolution of the Earth is the radiogenic heat, ~90% of which comes from the decay of ^{238}U and ^{232}Th. The radiogenic heat is supposed to

Fig. 35. Map of the commercial nuclear power plants (which are indicated by circles) around Kamioka.

contribute approximately half of the measured total heat dissipation rate from the Earth, which is 44.2 ± 1.0 or 31 ± 1 trillion watts (TW), depending on the analysis. Another one half is believed to come from the primordial energy of planetary accretion and latent heat of core solidification. The initial idea to use large liquid scintillator detectors to detect geo-neutrinos was reported in 1998 [73]. In 2005, KamLAND detected geo-neutrinos [74]. Figure 38 shows the updated energy spectrum of geo-neutrino events [75]. The data are consistent with the geo-scientific expectation within the experimental accuracy. This observation opened a new scientific field of "neutrino geo-science".

KamLAND steps forward in the new project named KamLAND-Zen, which searches for the neutrinoless double-beta decay with ^{136}Xe nuclei [76]. KamLAND

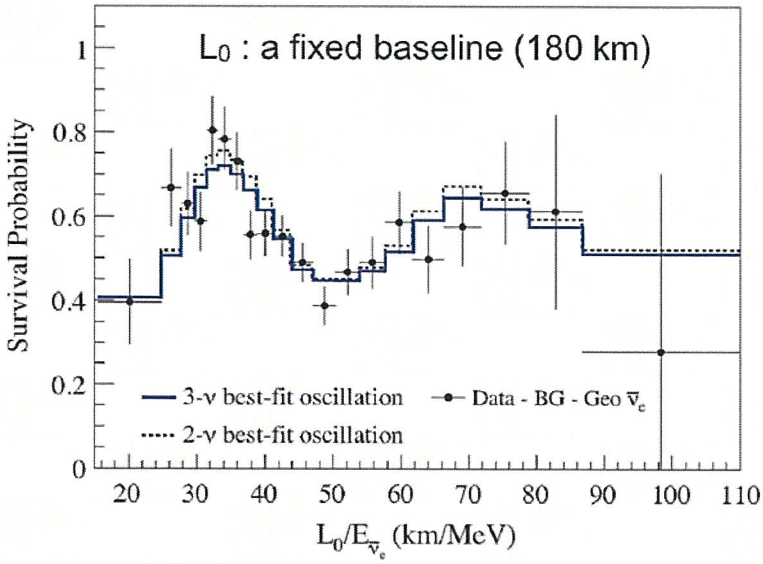

Fig. 36. Data from KamLAND, which shows (data/no-oscillation expectation) as a function of L/E [72].

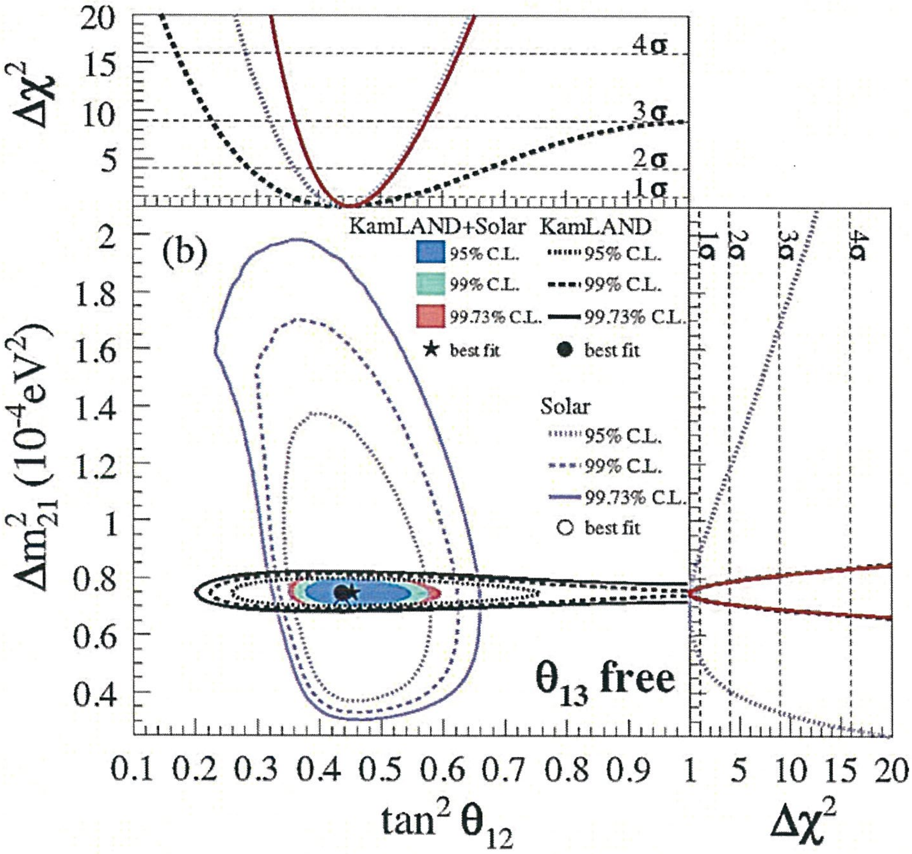

Fig. 37. Allowed region of 2-flavor $\nu_e \rightarrow \nu_x$, where ν_x represents ν_μ and ν_τ, oscillation parameters assuming that θ_{13} is a free parameter [72].

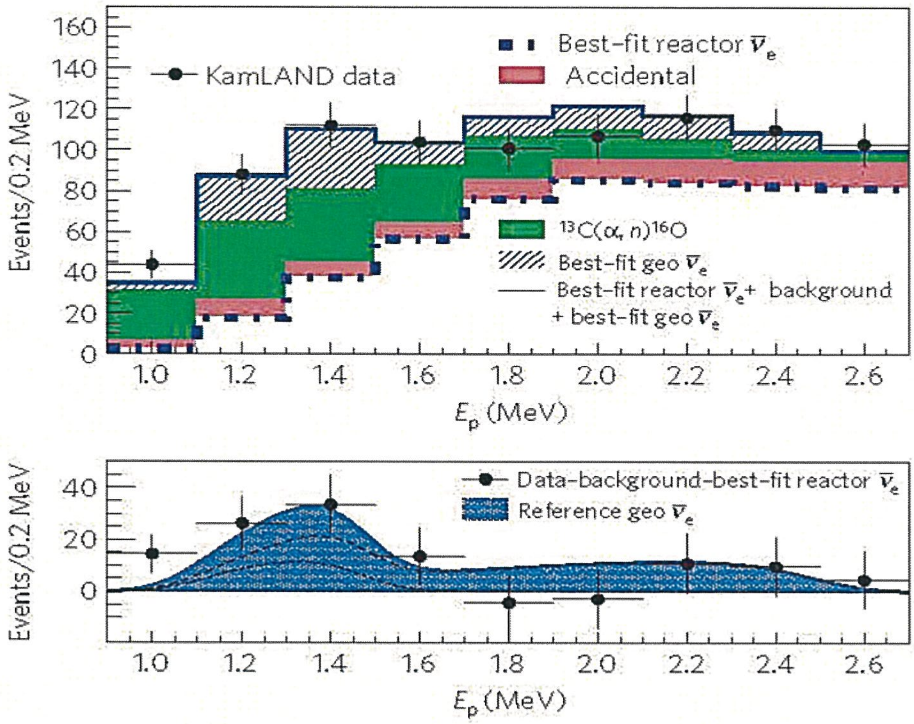

Fig. 38. Energy spectrum of the events observed in KamLAND in the energy range relevant to geo-neutrinos [75]. In the predicted geo-neutrino contribution, neutrino oscillations are taken into account.

has achieved very low radioactive impurity level of 3.5×10^{-18} g/g for ^{238}U and 5.2×10^{-17} g/g for ^{232}Th. This level is several orders of magnitude cleaner than that of previous double-beta decay experiments. Moreover, KamLAND holds 1000 ton of liquid scintillator and thus loading tons of double-beta decay nuclei in the scintillator seems to be feasible. Utilizing these features, KamLAND intends to reach the world best sensitivity for the double beta-decay search.

In designing the experiment, the following backgrounds should be addressed: cosmic-ray muon spallation backgrounds, especially ^{10}C, radioactive impurities, especially ^{214}Bi and ^{208}Tl, two neutrino double-beta decay and solar ^{8}B neutrinos. Simulating the above background turned out that 400 kg of 91% enriched ^{136}Xe reaches the sensitivity down to 60 meV, which corresponds to the degenerated neutrino-mass case fully. In the next step of KamLAND2-Zen (Xe:1000 kg), light reflection mirrors around PMTs will be attached for gaining a better energy resolution and the sensitivity will reach better than 30 meV, covering the inverted neutrino-mass hierarchy.

The schematic view of KamLAND-Zen is shown in Figure 39. The new Xe loaded-liquid scintillator balloon was installed at the center of the present KamLAND detector. The data-taking started in the middle of September, 2011. The achievable mass-sensitivity is shown in Figure 40 as a function of the dates of year, comparing with other on-going and planned double beta-decay experiments.

13 Present and future scientific activities in Kamioka

In this article, we discussed the history of Kamiokande together with those for its successors, Super-Kamiokande and KamLAND. At present, there are several other

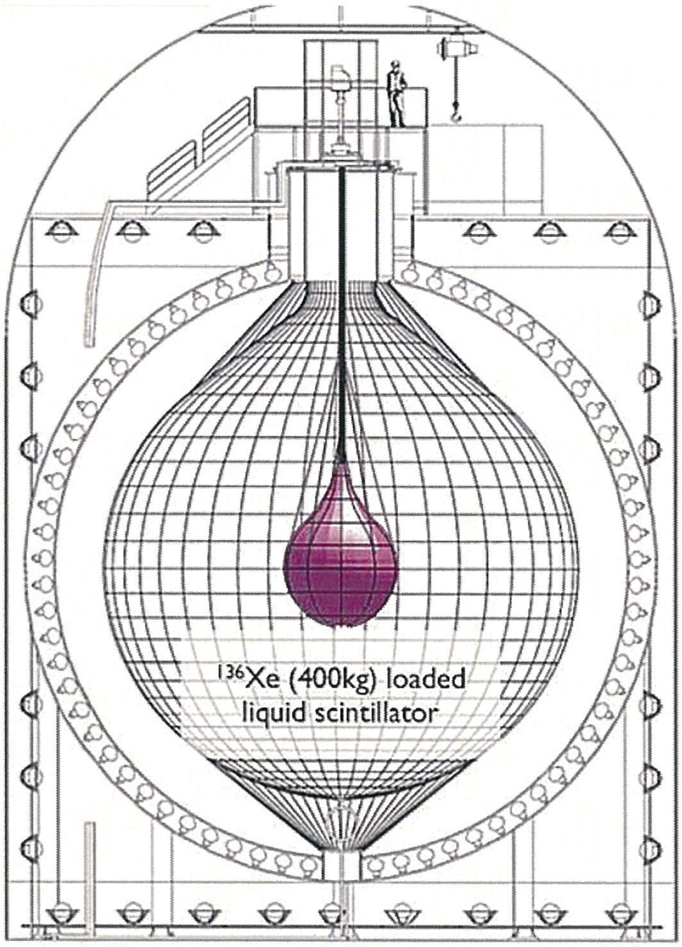

Fig. 39. Detector concepts of KamLAND-Zen.

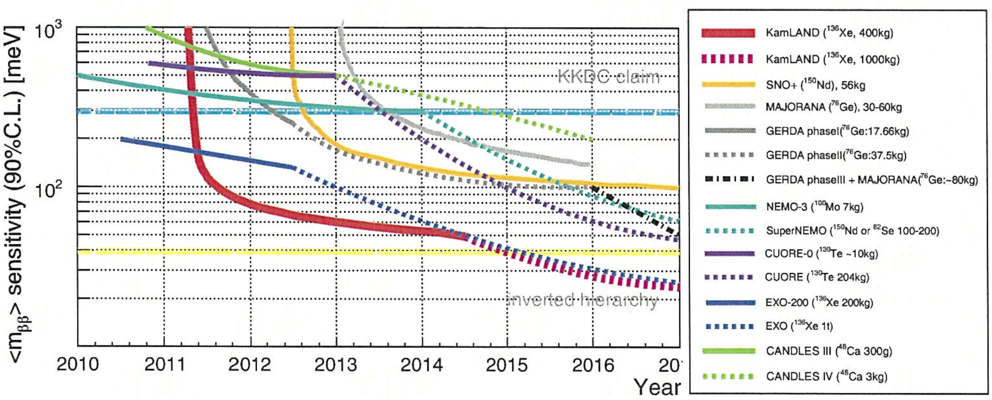

Fig. 40. Expected neutrino-mass sensitivity at 90% C.L. for current and future projects. KKDC stands for the positive evidence claimed in [77].

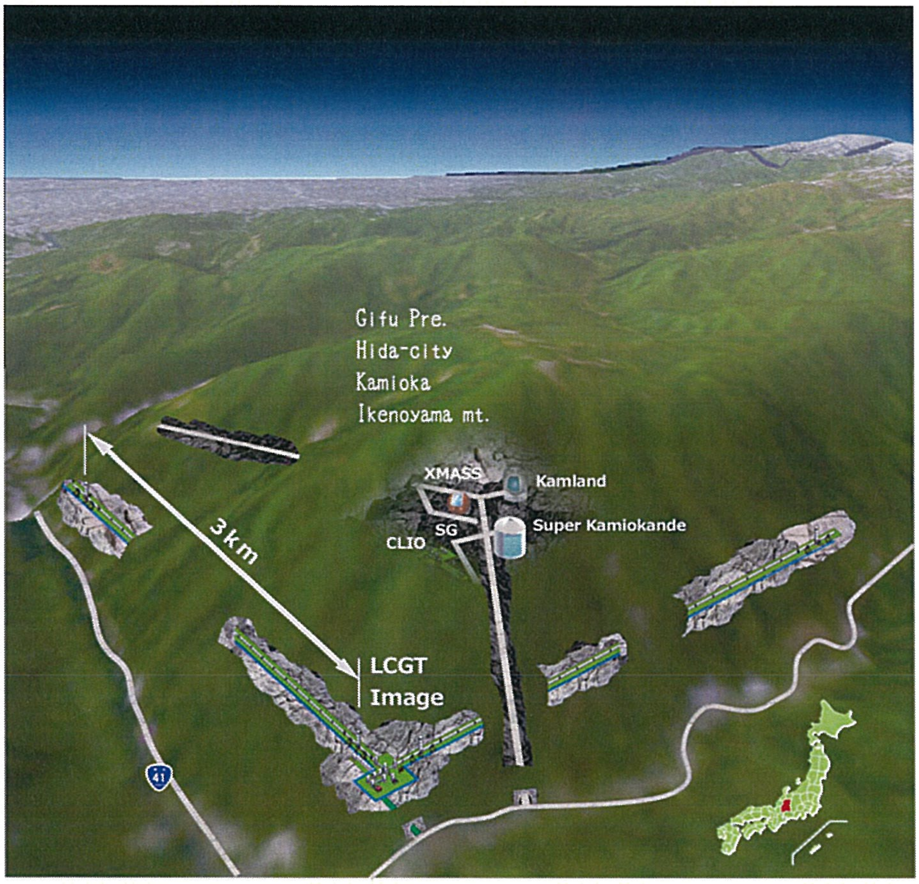

Fig. 41. Bird's-eye view of present and near-future experiments in Kamioka.

scientific activities in Kamioka underground. XMASS [78] is an experiment searching for signals of dark matter scattering off the ordinary matter. It uses 800 kg of liquid xenon. A dark matter scattering in the detector will produce scintillation light in the energy region of 10 keV. This experiment has been taking data since 2010. CANDRES [79] is a double beta decay experiment with 300 kg of Ca (^{48}Ca, which has the natural abundance of 0.2%, is the target) being the target nucleus for the double beta decay. This experiment will start taking data soon.

In addition to these underground astroparticle physics experiments, there is a facility for the R&D on the cryogenic technique for the detection of gravitational waves. This facility successfully demonstrated the improvement of the sensitivity with the operation of the interferometer with the cryogenic temperature [80]. With the success of this R&D, the construction of Large-scale Cryogenic Gravitational-wave Telescope (LCGT, recently it was renamed to KAGRA) [81] was approved in 2010. It will be a 3 km $\times$ 3 km interferometer with cryogenic mirrors, which will be located in Kamioka underground. It is expected that this interferometer will be able to detect approximately 10 gravitational wave events per year from the merger of two compact objects such as neutron starts or black holes. Coincidence detections of supernova signals by both gravitational waves (KAGRA) and neutrinos (Super-Kamiokande) are also expected. The KAGRA interferometer is expected to start taking data in 2018. Figure 41 shows the location of present and near-future experiments in Kamioka. Kamioka has been developed to a general underground laboratory with various experiments.

The successes of the Kamiokande and Super-Kamiokande experiments motivated the next generation neutrino detector in the Kamioka area. This detector is called Hyper-Kamiokande [82]. It will be a very large water Cherenkov detector with the total mass of about 1 Mton. The motivation for this detector is to study the CP violation (violation of Charge conjugation and Parity) in the neutrino sector experimentally. It is known that the CP violation in the neutrino sector might be the key to the understanding of the baryon asymmetry of the Universe. If CP is not conserved, oscillations of neutrinos and anti-neutrinos should be different. In order to observe this effect, one needs to carry out an oscillation experiment with a very large neutrino detector using a very strong neutrino beam.

14 Summary

Underground experiments have been playing essential roles in the recent development of neutrino physics, astro-physics and geo-science. In particular, the role of Kamiokande was very important. This experiment observed neutrinos from Supernova SN1987A confirming the basic mechanism of the supernova explosion, and neutrino from the Sun, confirming that the neutrinos are indeed coming from the Sun. The observation of solar neutrinos by Kamiokande also confirmed the deficit of the solar neutrino flux. In addition, Kamiokande discovered the deficit of the atmospheric muon-neutrino flux relative to the electron-neutrino flux.

Super-Kamiokande and KamLAND experiments are the second and the third generation neutrino experiments at Kamioka. Super-Kamiokande confirmed that the deficit of the atmospheric muon-neutrino flux was due to neutrino oscillations by clearly observing the zenith-angle dependent deficit of the atmospheric muon-neutrinos. It was concluded that the deficit of the solar neutrino flux was due to neutrino oscillations by the SNO, Super-Kamiokande and KamLAND experiments. In particular, KamLAND clearly observed the oscillation pattern in the reactor neutrino spectrum.

Although we did not cover in detail the worldwide efforts of developing neutrino physics and astrophysics, there have been many activities of fundamental importance. We conclude that the fields of neutrino physics, astro-physics and geo-science are growing rapidly. We hope that future underground experiments in Kamioka will continue contributing to the developments of these fields substantially.

Acknowledgements. The authors would like to acknowledge the colleagues in Kamiokande, Super-Kamiokande and KamLAND. We also acknowledge the generous cooperation of the Kamioka Mining and Smelting Co. The Kamiokande, Super-Kamiokande and KamLAND experiments have been supported by the Japanese Ministry of Education, Culture, Sports, Science and Technology, together with supports from founding agencies of many collaborating countries.

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