4.2 Experiments at the 12 GeV Proton Synchrotron

In FY2001, the operation of the KEK 12 GeV Proton Synchrotron (PS) started in April 2001 in the fast beam-extraction mode and the K2K experiment took data through July 2001. After the summer shutdown, the PS operation was resumed in the slow extraction mode and five experiments were run until March 2002. Out of these five experiments, four experiments, E325, E452, E462, and E470, finished their data taking in FY2001.

Experiment E246 is searching for T-violating muon polarization in $K^+ \rightarrow \pi^0\mu^+\nu$ ($K_\mu 3$) decays. In FY2001, the group concentrated on data analysis. They reviewed the systematic errors of their 1998 results and analyzed new data from 1999 and 2000. A preliminary result has been obtained and will be reported elsewhere. The group also studied $K^+ \rightarrow \pi^0 e^+\nu$ (K_{e3}) decays to further constrain the exotic scalar and tensor couplings. The group has obtained f_s/f+(0) = 0.0040 ± 0.0160(statistical) ± 0.0067(systematic) and f_T/f+(0) =0.019 ± 0.080(statistical) ± 0.038(systematic). They have also looked at the ratio $\Gamma(K_{e3})/\Gamma(K_{\mu 3})$ and obtained the q^2-dependent coefficient λ_0 of the $f_0(K_{l3})$ form factor as λ_0 = 0.019 ± 0.005(statistical) ± 0.004 (systematic).

To study the direct emission component in radiative K^+ decays, $K^+ \rightarrow \pi^+\pi^-\gamma$, the same group proposed a new experiment designated E470 using the E246 detector but with optimized triggers. Radiative K^+ decay is dominated by the inner bremsstrahlung, that is, the QED radiative correction to $K^+ \rightarrow \pi^+\pi^0$ decay, and the direct emission is to be found as a deviation of the measured spectrum from the inner bremsstrahlung spectrum. The direct emission is interesting because its magnetic component originates in the chiral anomaly and may be calculated by low energy effective theories such as the chiral perturbation theory. The E470 experiment collected data for 120 shifts in autumn 2001. The branching ratio of the direct emission is expected to be O(10^{-5}) and the statistical accuracy of this experiment to be around 10%.

The E325 experiment is the oldest among the active experiments at the KEK PS. It was approved in 1995 and started physics runs in 1997. Since then, the total beam time has exceeded 400 shifts. In FY2001, the experiment finally completed its data taking. The objective of the experiment is to find signatures of mass shifts of vector mesons decaying in the nuclear matter of normal density. It measures both K^+K^- and e^+e^- decays of ϕ mesons produced in 12 GeV proton interactions with nuclei. The earlier results of the experiment have shown a signature of the mass shift in the e^+e^- decay mode. The experiment is now moving to the final analysis stage.

The hybrid emulsion experiment E373 studies the singlet 1S sector of a doubly strange system. The physics interest is a unified description of the baryon-baryon interaction by the $SU(3)_f$ symmetry. About 40% of the data so far taken have been analyzed and 103 Ξ hyperon stopping events have been found. Among them there are two events of sequential decay topology of a double-Λ hypernucleus. One of the two events has the topology of formation and decay of a ${}^{6}_{\Lambda\Lambda}He$ nucleus. This event confirms the attractive ΛΛ interaction with the binding energy $\Delta B_{\Lambda\Lambda}$ = 1.01 ± $0.20^{+0.18}_{-0.11}$ MeV. The other event, a twin single-Λ hypernuclei event, shows a very clean topology as seen in Fig. 4-2-1. From these type of events, the binding energy of Ξ^- in nuclei should in principle be calculable. Unfortunately, one track (#5 in Fig. 4-2-1) of the event escaped from the emulsion stack and is not recorded in the fiber-block detector; therefore, the reconstruction of the event is not unique. The group is now investigating three possible interpretations of the event.

Experiment E391, which has now been renamed E391a, is searching for the CP-violation effect in $K^0_L \rightarrow \pi^0\nu\bar{\nu}$ rare decays. The group has been expanded significantly since last year and is now an international collaboration with physicists from Japan, Korea,

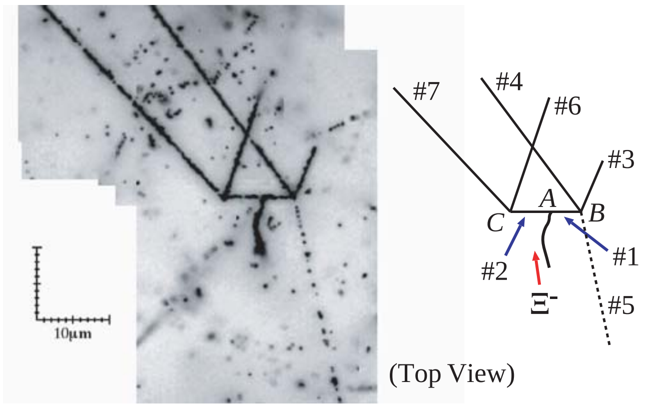

Fig. 4-2-1 Emulsion image of the twin single-Λ hypernuclei event (left) in E373. The event topology is also shown (right).

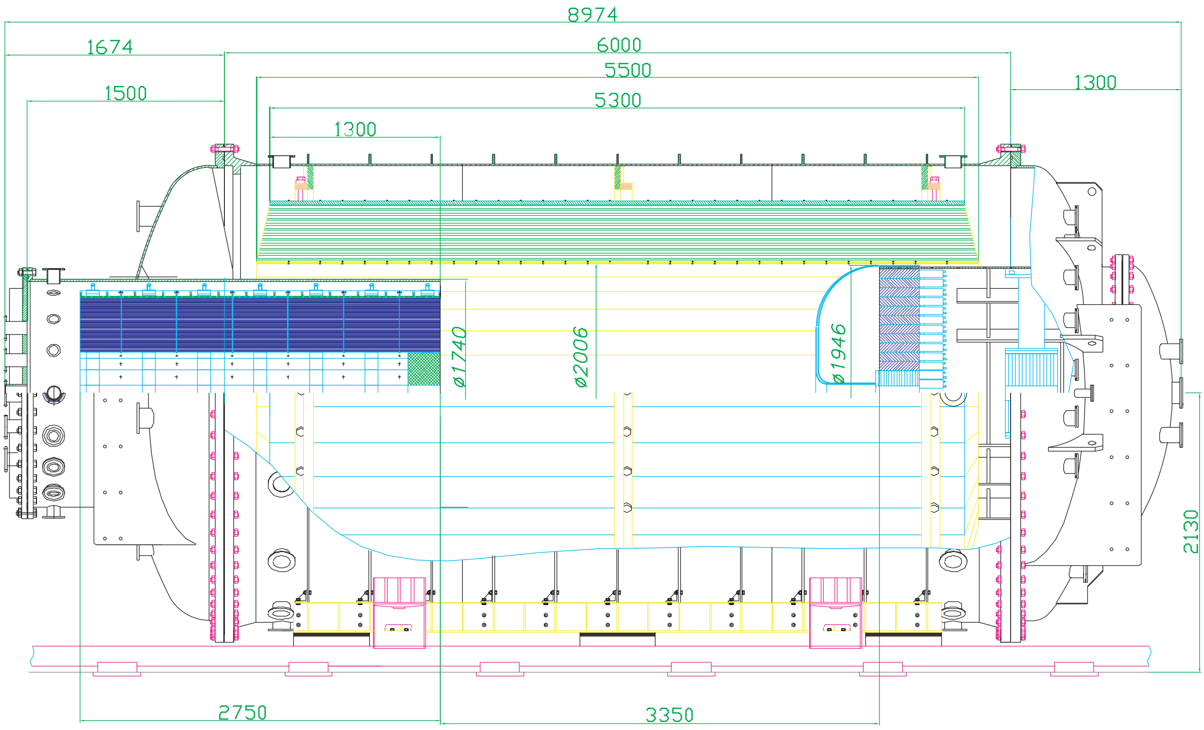

Fig. 4-2-2 Engineering design of the E391a detector to measure $K_L^0 \to \pi^0 \nu \bar{\nu}$ rare-decays. Most of the detectors including a CsI calorimeter are placed inside one large vacuum vessel.

Fig. 4-2-3 Downstream section of the E391a vacuum vessel placed in the PS experimental hall.

Russia, and the United States. In FY2001, the group conducted an extensive engineering study of the detector system in collaboration with a Russian design company. The design has been almost finalized as shown in Fig. 4-2-2. Most of the detectors are placed inside one large vacuum vessel that consists of three sections: upstream section, middle section, and downstream section. The downstream section was fabricated in FY2001 (Fig. 4-2-3). The main detector of the experiment, CsI crystal calorimeter, will be mounted on it and tested in autumn 2002. The experiment foresees pilot runs at the KEK PS starting in FY2003 and then a high statistical experiment at the JHF 50 GeV PS (HIPA) in the future.

In order to study the spin-orbit interactions of the hyperon-nucleon system, experiment E452 is measuring the left-right asymmetries of the Σ^+ and Λ elastic scatterings on protons. Polarized Σ^+ and Λ were produced through (π^+, K^+) interactions in an active liquid-scintillator target at p_π =1.6 GeV/c. The polarization of Σ^+ was known to be as large as 0.8 (Fig. 4-2-4 (a)) from previous experiments. The polarization of Λ was measured and found to be also large in this experiment (Fig. 4-2-4 (c)). In the experiment, candidates for the hyperon event were selectively recorded

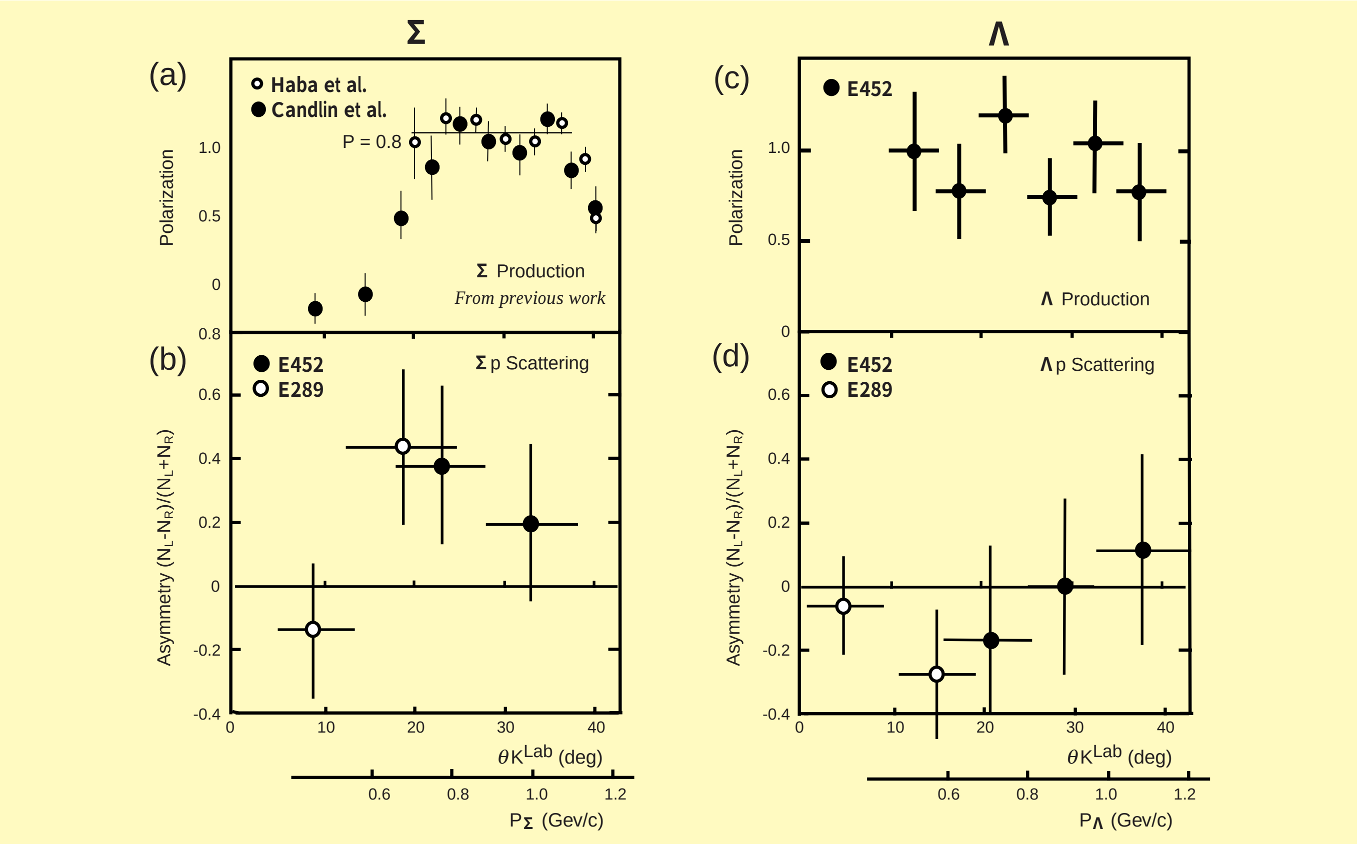

Fig. 4-2-4 E452 measured polarizations of Σ (a) and Λ (c) produced in (π^+, K^+) interactions (top) and left-right asymmetries of the Σ^+p (b) and the Λp (d) elastic scatterings (bottom).

by the SCIntillating Track Image Camera (SCITIC) with a kaon trigger signal from the forward spectrometer. The experiment started in FY2000 and finished data taking in February 2002. About 800k hyperon event candidates were recorded. The immediate interest of the experiment is to compare the spin-orbit interaction between the Σ^+p and Λp elastic scatterings. So far only 10% of the events have been analyzed. Preliminary results of the left-right asymmetries of the Σ^+p and the Λp elastic scatterings are shown in Fig. 4-2-4 (b) and (d), respectively. Reanalyzed data from the previous experiment E289 are included here. A larger spin-orbit interaction is seen in the Σ^+p scatterings than in the Λp scatterings.

Beside the above five physics experiments, 23 test experiments were carried out in FY2001. Experiment T484 tested the basic performance of a new detector, called Time-Of-Propagation (TOP) counter, for a future Belle detector upgrade. It is a detector for particle identification using the spacetime information of Cerenkov lights emitted in quartz bars. Experiment T487 studied the feasibility of using an Emulsion Cloud Chamber (ECC) to measure charged particle momentum and thereby identify electrons. The goal is to develop a new technology to measure neutrino flux. The momentum resolution measured by multiple scatterings in the ECC was found to be about 20%. The T489 group has been developing a position-sensitive Cerenkov detector (POSCH) for the search of η and ω mesonic nuclei at GSI and the T494 group tested the performance of prototype detectors for a new spectrometer to be used in (e,e'K^+) Λ-hypernuclei spectroscopy at the Jefferson Lab. The former group has obtained good p/K^+ separation by a pure-water Cerenkov counter (Fig. 4-2-5). To improve the particle identification capability of the PHENIX experiment at BNL-RHIC, the T496 group tested aerogel Cerenkov counters (Fig. 4-2-6). Together with TOF and RICH, an aerogel Cerenkov counter of n = 1.01 provides good π/K/p identification up to 10 GeV/c without any momentum gap. The T499 group has been designing an experiment to measure Auger electrons emitted in the π capture and electronic X-rays (eX-rays) in coincidence with pionic X-rays (πX-rays). In FY2001, they

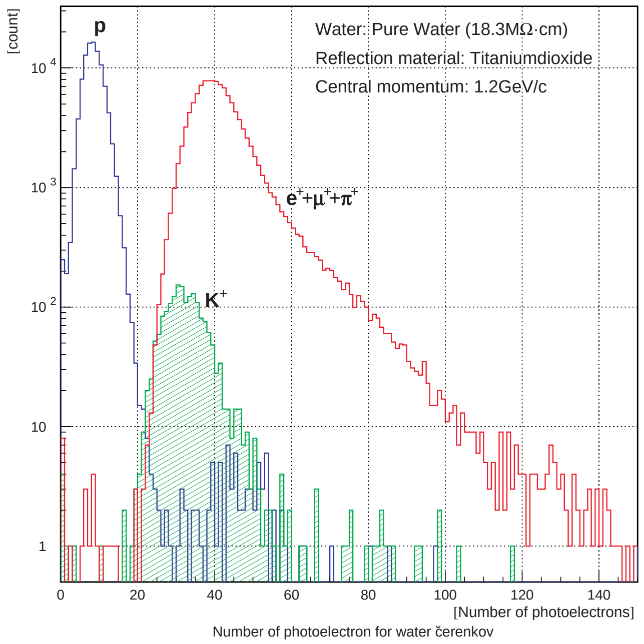

Fig. 4-2-5 Number of photoelectrons measured by the T494 pure-water Cerenkov counter. More than 99% of protons are separated without missing K^+s.

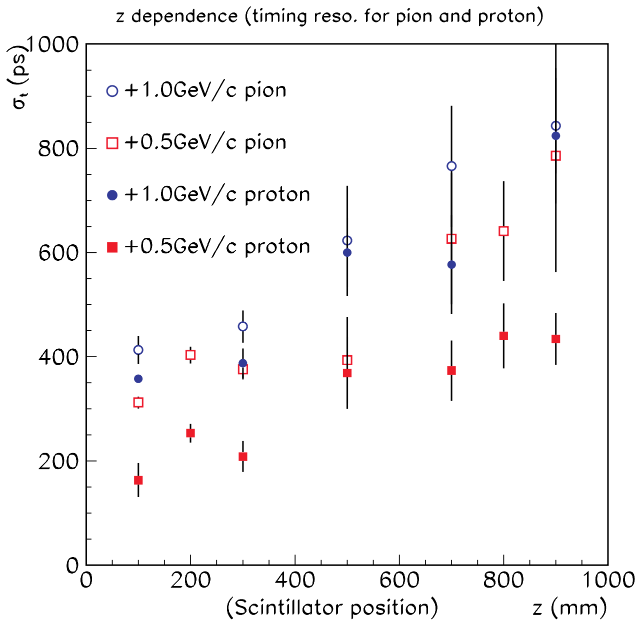

Fig. 4-2-7 TOF resolutions obtained by a fine-segmented TOF hodoscope (5 mm × 10 mm × 1,000 mm) made of fiber bundles read out by multi-anode PMTs (T502).

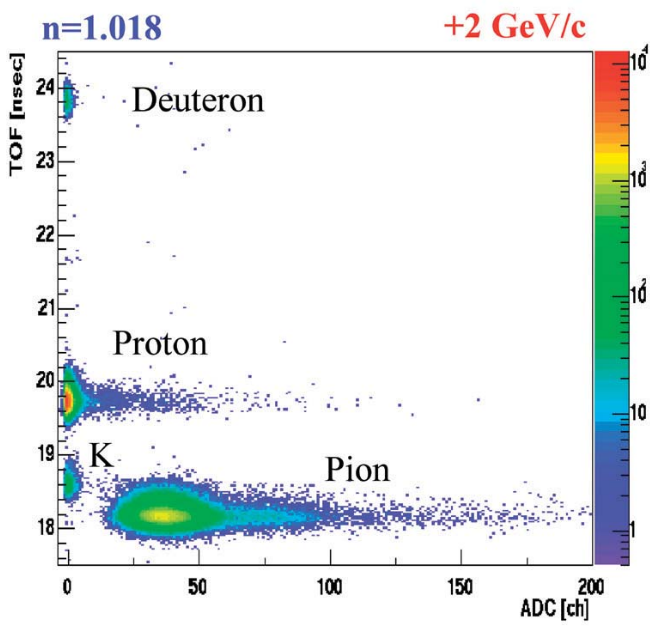

Fig. 4-2-6 Study of particle identification by a combination of aerogel counter and TOF for the PHENIX experiment (T496).

measured the eX- and πX-rays using a pair of Ge-detectors for low-energy photon spectrometry. The T502 group tested the performance of two drift chambers and a scintillation fiber detector for the BESS 2002 balloon-borne experiment. Also tested was a new TOF counter of fiber-bundles for the BESS-Polar experiment. The timing resolution of the TOF counter was found to be 0.2−0.6 ns, which is sufficient to separate $\overline{p}$ from negatively charged low-energy muons (Fig. 4-2-7). For an upgrade of the K2K near detector, four test experiments were performed. Experiment T488 tested a tracking detector consisting of plastic-scintillator plates with wavelength-shifting (WLS) fibers. The scintillator plates are doped with light-scattering material to improve the position resolution while maintaining good detection efficiency. Experiments T491 and T503 tested the basic performance of a scintillator tracker called SciBar. The tracker uses extruded scintillators read out by wavelength-shifting fibers. And experiment T501 was conducted to calibrate the energy scale of the neutrino spectrum measured in the present K2K near detector.

4.3 K2K Experiment

The KEK-to-Kamioka (K2K) long-baseline neutrino oscillation experiment is the first accelerator-based experiment with a neutrino path length of hundreds of kilometers. The intense, nearly pure neutrino beam (98.2% ν_μ, 1.3% ν_e, and 0.5% $\overline{\nu}_\mu$) has an average $L/E_\nu \sim 200$ (L = 250km, $< E_\nu > \sim 1.3$ GeV). The K2K experiment focuses on studying the existence of neutrino oscillation in ν_μ disappearance, which was observed for the first time in atmospheric neutrinos, and on the search for $\nu_\mu \to \nu_e$ oscillation with the KEK neutrino beam, whose flux and neutrino composition have been well studied in the $m^2 \geq 2 \times 10^{-3}$ eV^2 region.

In FY2001, the K2K experiment took data from April to July. Since the start of the experiment in 1999, the total number of protons delivered on the pion production target (protons on target: POT) has reached 5.6×10^{19}. The net POT successfully used for the analysis of the Super-Kamiokande (SK) data is 4.8×10^{19}. The balance is due to various reasons: tuning of the beam channel and its horns, calibration of the Super-Kamiokande, power failure at the Super-Kamiokand, and failure in the online data acquisition of the beam-monitoring data. As of July 2001, the K2K experiment is still midway toward its original goal of 10^{20} POT.

With all the available data analyzed, 56 neutrinos coming from KEK were observed inside the Super-Kamiokande fiducial volume of 22,500 tons of water, while, from the observations with the 1,000-ton water Cerenkov detector located at the KEK site, $80.6^{+7.3}_{-8.0}$ neutrino events were expected to be observed if neutrinos did not oscillate. Table 4-3-1 compares these results with the expected number of events calculated for the maximal neutrino oscillation ($sin^2 2\theta = 1$). The table also includes numbers for 1-ring μ-like and e-like events and multi-ring events.

Figure 4-3-1 shows the overall history of event arrival time through all runs. The horizontal axis represents POT rather than the elapsed time. The uniformity of the arrival time was tested by the Kolmogoroff-Smirnov (KS) probability and found to be 43.1%, indicating a satisfactorily uniform distribution.

The goal of the oscillation analysis is to compare the spectrum observed at the Super-Kamiokande to those extrapolated from the spectrum measured at the

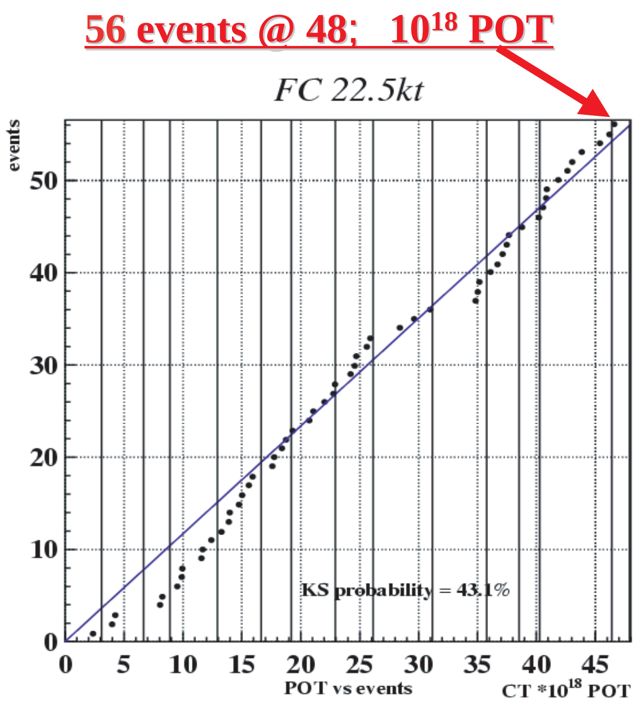

Fig. 4-3-1 POT (number of protons delivered onto the target) versus accumulated number of events at the Super-Kamiokande.

Table 4-3-1 Observed numbers of the fully-contained (FC) events in the SK with the vertices located inside the 22,500-ton fiducial volume (FV) compared to the two expected numbers calculated from the observations in the 1,000-ton water Cerenkov detector at the KEK site for no oscillation and for neutrino oscillation with $\sin^2 2\theta = 1$

	$N_{SK}^{observed}$	Null oscillation	Δm^2 (eV^2)		
			3×10^{-3}	5×10^{-3}	7×10^{-3}
FC event in FV	56	$80.6^{+7.3}_{-8.0}$	52.4	34.6	29.2
1-ring	32	48.4 ± 6.7	28.1	17.8	16.0
μ-like	30	44.0 ± 6.8	24.4	14.6	13.5
e-like	2	4.4 ± 1.7	3.7	3.2	3.0
Multi-ring	24	32.2 ± 5.3	24.3	16.8	12.6

near detector with and without neutrino oscillation. Figure 4-3-2 shows the reconstructed E_ν spectrum of 30 fully contained 1-ring μ-like events in the Super-Kamiokande fiducial volume. Here, the kinematics of a two-body quasi-elastic (QE) reaction are assumed. The observed spectrum, therefore, mostly consists of real muon neutrinos and non-QE background. The figure also shows the spectrum extrapolated from the measurement at the near detector. The non-QE background is estimated by a Monte Carlo simulation with detector response. It should be noted that the neutrino oscillation with $\Delta m^2 = 3 \times 10^{-3}$ eV^2, which is consistent with the atmospheric neutrino oscillations, predicts the oscillation minimum in the E_ν spectrum at about 600 MeV. Although the systematic errors associated with the data and the extrapolation of the spectrum are very preliminary, the data, which also include the non-QE background, seem to present the minimum at the right E_ν energy.

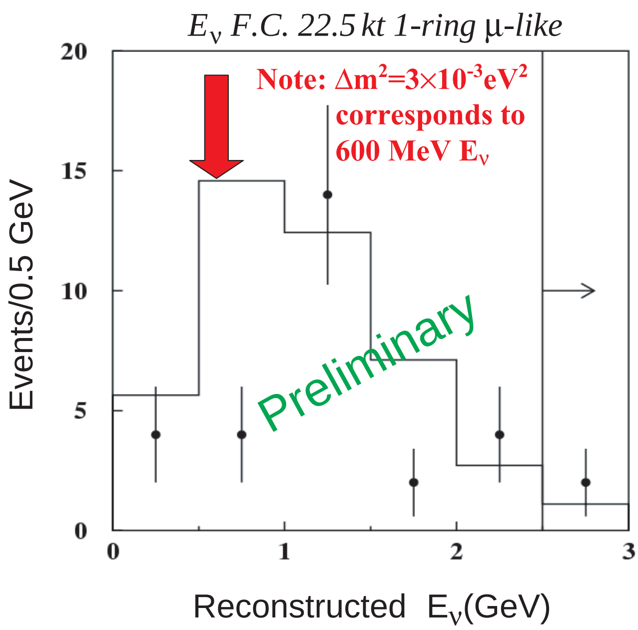

Fig. 4-3-2 The neutrino spectrum observed at the Super-Kamiokande. The histogram shows the spectrum extrapolated from the observation at the near detector assuming no neutrino oscillation (preliminary).

On November 12, 2001, the Super-Kamiokande, the far detector of the K2K experiment, suffered from a sad accident, in which about 60% of both the 20-inch photo-multiplier tubes (PMTs) for the inner detector and the 8-inch PMTs for the outer detector were destroyed. Before the accident, the Super-Kamiokande had been drained since July 2001 after five years of operation and dead PMTs replaced with new ones. The accident occurred when water was being filled after the maintenance work was completed. The water level at the time of the accident was about 30 m. The cause of the accident was investigated and found to be the implosion of one PMT of the inner bottom PMT plane. The implosion generated shock waves that destroyed neighboring PMTs, resulting in a chain reaction and thereby the mass destruction of PMTs. It is speculated that the first PMT that imploded was one that suffered slight damage to the PMT glass when it was installed as a replacement for a dead PMT or one that was subjected to strain when nearby bottom PMTs were replaced.

As a result of the accident, the K2K runs originally scheduled after January 2002 had to be deferred. As the spokesperson for the Super-Kamiokande Collaboration, Professor Totsuka, announced immediately after the accident, in order to resume the K2K experiment at the earliest possible time, possibly within a year, it was decided to rebuild the Super-Kamiokande with existing PMTs; that is, with a PMT density of about one-half the original density. It should be noted, however, that for the detection of GeV neutrinos from KEK, the reduced PMT density should not cause any serious deterioration of the detector performance.