4.2 Experiments at the 12 GeV Proton Synchrotron

In FY2003, the KEK 12 GeV Proton Synchrotron (PS) was operated mainly in fast beam-extraction mode to compensate for the suspension due to rebuilding work of photomultiplier tubes (PMTs) at a Super-Kamiokande in FY2002. The slow beam-extraction mode was operated for two weeks before the summer shutdown and for one and a half months at the end of FY2003. During the period in slow beam-extraction mode, six experiments and 12 tests were performed.

E391a is the first experiment dedicated to a flavor-changing neutral current (FCNC) process, the $K_L \rightarrow \pi^0\nu\bar{\nu}$ decay. Almost all of the detectors are installed in a vacuum (Fig. 4-2-1). The detector system consists of 576 CsI calorimeters to measure the two gammas from $K_L \rightarrow \pi^0\nu\bar{\nu}$, and sampling calorimeters surrounding the decay fiducial region to veto the other decays and beam backgrounds. The vacuum level reaches less than 1×10^{-1} Pa in the detector region and less than 2×10^{-5} Pa around the beam region. Data taking was started on schedule in February 2004, and will be continued up to the end of June 2004. The experiment will reach the goal sensitivity of O(–10) for the $K_L \rightarrow \pi^0\nu\bar{\nu}$ decay.

The extension of the beam time was approved for two experiments: the search for a deeply bound K^-ppn state (E471), and production of neutron-rich Λ hypernuclei by the (π^-, K^+) double-charge-exchange reaction (E521). A promising enhancement in the neutron spectrum of E471 found in the FY2002 data will be located by increasing the statistics. E521 continued with the beam momentum at 1.2 GeV/c to establish the ${}^{10}_{\Lambda}$Li production and accumulated data for another 700×10^9 π^--injections. The search for H-dibaryon resonance via ${}^{12}C(K^-, K^+\Lambda\Lambda)$ (E522) was performed to compensate for the loss of beam time in FY2002. The invariant mass spectrum of ΛΛ near the threshold (Fig. 4-2-2) shows the enhancement, which could be attributed to the attractive final-state interaction of ΛΛ. In E546, the electronic X-ray emission correlated with each pionic X-ray was measured to understand electronic rearrangement in the pionic atom during the pionic cascade. To examine the correlation between πX-rays and eX-rays, the photon events, Mo, Sn, Dy, Ho, Ta, and Pb metals, and Mo, Sn, Ba, Nd, Gd, Ho, Yb, and Hg oxides were used as the target. For these four experiments, data taking has been completed.

Test experiments were carried out in FY2003 for calibrations and R&D of detectors, not only for PS experiments but also for experiments at other laboratories and future experiments. The T526/542 group for the international Muon Ionization Cooling Experiment (MICE) at RAL has tested the basic performances of scintillating fiber trackers to minimize the effects of

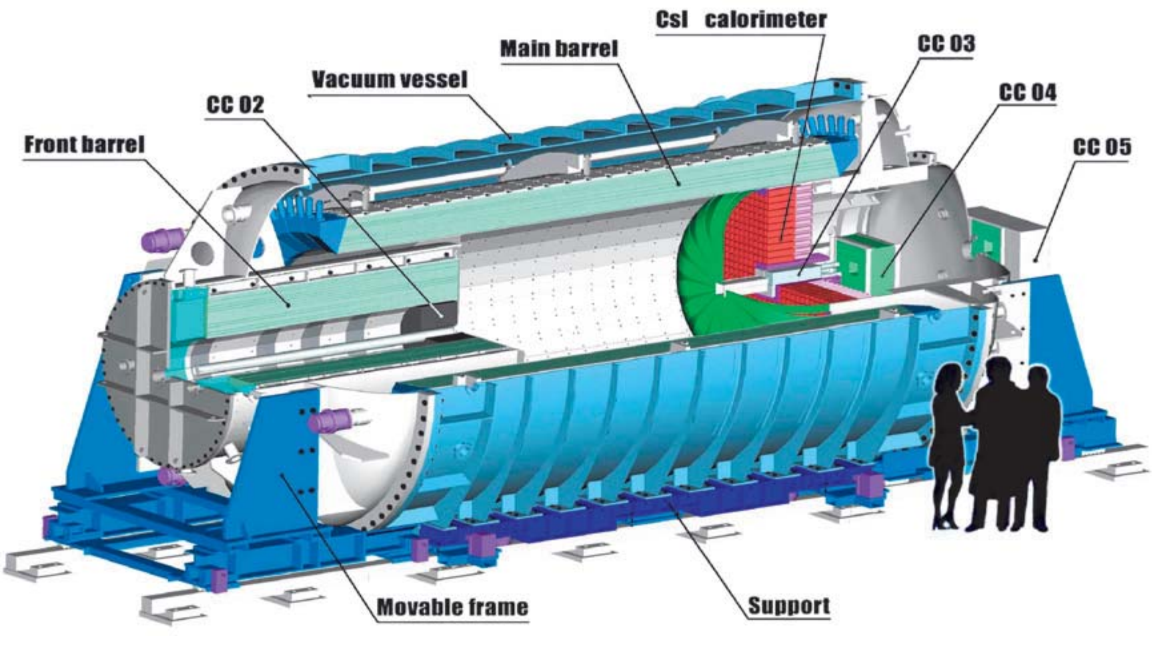

Fig. 4-2-1 E391a detector system.

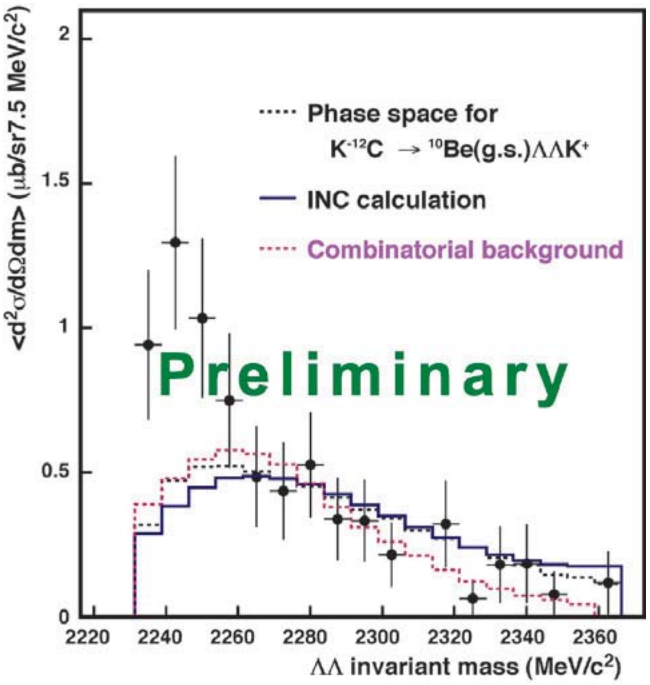

Fig. 4-2-2 Invariant mass spectrum of ΛΛ near the threshold in E522. The statistical significance of the enhancement below the 2261 MeV/c^2 region was found to be 2.7 standard deviations with respect to the combinatorial background.

Fig. 4-2-3 Director Totsuka discussing with Dr. Evtoukhovitch (JINR), Prof. Mjavia (JINR), Dr. Garutti (DESY), and Prof. Takeshita (Shinshu Univ.).

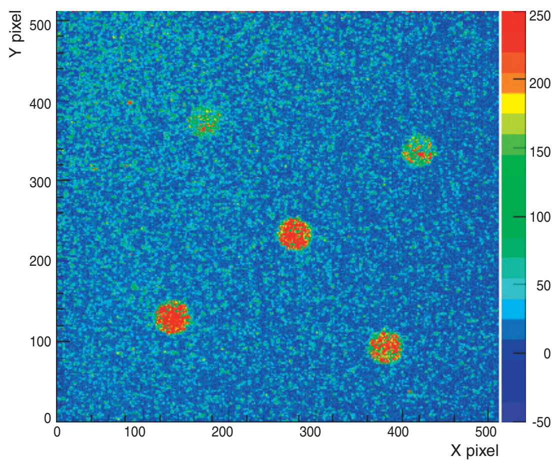

Fig. 4-2-4 Image of fibers measured with EBCCD.

background X rays from RF cavities and multiple scattering. The purpose of T538 was R&D of the Time Projection Chamber with CF_4 gas for heavy ion collisions at BNL. Tracking resolution, double track separation, and particle identification capability were tested and a 100 μm position resolution with a 2.5 mm square pad was achieved. The T539 group has been developing beam monitoring detectors in the intermediate beam intensity from 10^8 to 10^{10} particles/spill in the secondary beam line at J-PARC. Stable operation of the fiber detectors (glass and scintillating fibers) in the secondary beam line was confirmed, at least up to about 5M particles/spill/fiber. The T540 group verified the performances of the prototype particle detectors for the newly developed BESS-Polar superconducting spectrometer. A timing resolution of the scintillation counter hodoscope of below 250 ps for each pad was obtained for 0.5 GeV/c protons, which is better than the designed value. The objective of T543 is to provide sample emulsion bricks to conduct a rehearsal of the event locations procedure for the OPERA experiment at CERN. A scintillating fiber tracker is used to determine the true location by tagging an incoming parent particle and outgoing daughter tracks. An extremely low intensity beam of about 1–10 particles/spill, which is required for this rehearsal, was found to be possible at the π2 beam line. The T545 experiment for very high granularity calorimetry for precise determination of the reaction final state in linear collider experiments was carried out as a collaboration with a group from JINR and a group from DESY. Figure 4-2-3 shows a scene in front of the JINR EMC module during the beam test in which Director Totsuka was discussing the tile fabricated by the JINR group using the injection-mold method. Figure 4-2-4 shows an example of a reconstructed image of EBCCD data with five-fiber readout for plastic-scintillator-based fine-granularity calorimeters. The T547 group has been studying a

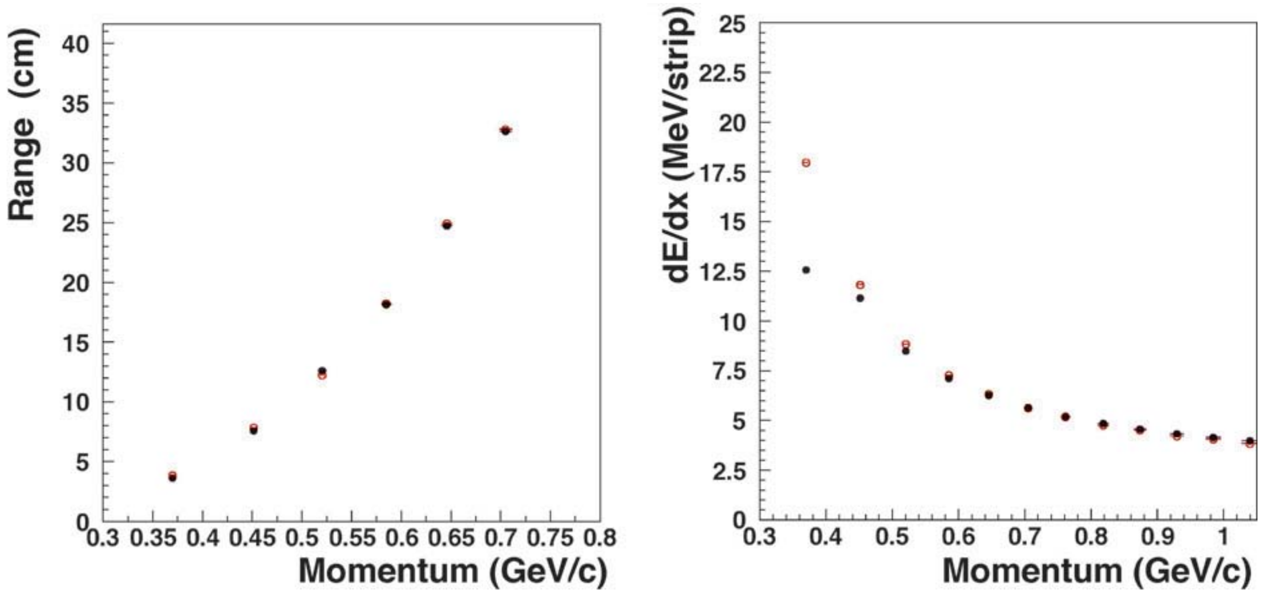

Fig. 4-2-5 Measured range (left) and dE/dx (right) of protons in scintillator as a function of momentum. Black (red) points represent data (MC simulation).

very high resolution time-of-flight counter that uses Cerenkov radiation from a quartz radiator. The test counter consists of the quartz radiator and a micro-channel-plate PMT. The purpose of experiment T551 is to measure the basic parameters of the scintillator used for the K2K SciBar detector, which was constructed in the summer of 2003 to upgrade the K2K near detector system. Figure 4-2-5 shows the measured range and dE/dx of protons as a function of momentum. The measured range shows excellent agreement with the Monte Carlo (MC) expectation, whereas a discrepancy is seen in the low-momentum region for dE/dx. This is presumably due to saturation and nonlinearity of the readout electronics for a large amount of charge, which is not included in the MC at this time. These data will give important information about the response of scintillators in the SciBar detector.

Several results have been obtained from executed experiments in the analysis stage. E246 has searched for a T-violating transverse muon polarization (P_T) in the $K^+ \rightarrow \pi^0\mu^+\nu$ decay. In 2003, the combination of two independent analyses was completed by sorting all good events into three categories: common events and two types of uncommon events. The null asymmetry A_0, the sensitivity A_N, and other systematics such as the decay plane angular distribution of each data set were carefully checked and it was confirmed that all the data were of high quality. For the polarimeter analysis, a new method has been adopted to explicitly take into account the muon stopping distribution in the stopper. In this analysis, P_T is extracted differentially along the polarimeter axis, and its averaging gives the result of $P_T = -0.0017 \pm 0.0023(stat) \pm 0.0011(syst)$ corresponding to $\mathrm{Im}\xi = -0.0053 \pm 0.0071(stat) \pm 0.0036(syst)$, which shows no evidence of T violation within the experimental accuracy. This result improved the previous limit from BNL-AGS by a factor of 3 as shown in Fig. 4-2-6, and can constrain the model parameters of several non-standard CP violation models.

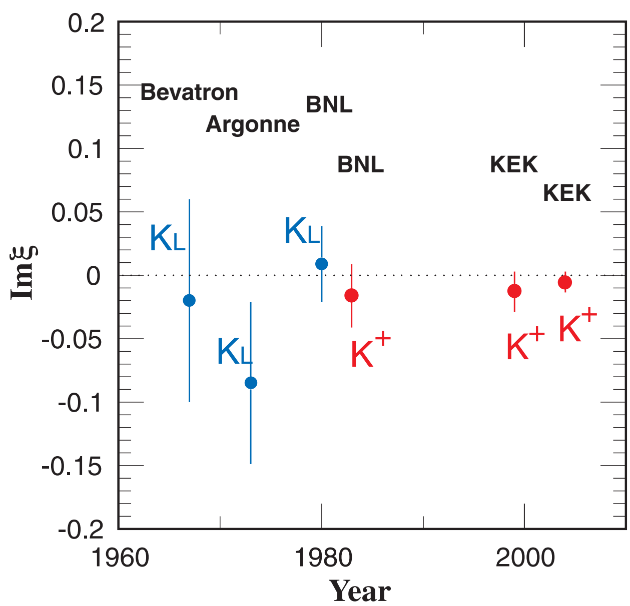

Fig. 4-2-6 History of P_T including E246 results.

The major scientific interest of E325 is to investigate the properties of hadrons (and then of quarks) in dense matter, naturally existing as nuclei. The basic experimental concept is to measure vector mesons, which are produced and decay in a nucleus, through invariant mass spectroscopy in the electron-positron pair channel. Figure 4-2-7 shows the electron pair spectrum for a copper target, after subtracting the combinatorial background. Free decay peaks of ω and ϕ are clearly observed and significant excess can be seen on the low mass side of the ω peaks.

In the analysis of the hybrid emulsion experiment E373, a clear event, "NAGARA", was detected as shown in Fig. 4-2-8. A Ξ^- hyperon was captured and three charged particles were emitted. Since each of the three charged tracks at two decay points was coplanar within angle errors, it was natural that no neutral particles were emitted. Kinematic analysis showed that only the modes of $\Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$, and ${}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$, satisfy the conditions for the production and decay of a double-Λ hypernucleus without any ambiguities by the excited state for the double- and single-Λ hypernucleus. $B_{\Lambda\Lambda}$ and $\Delta B_{\Lambda\Lambda}$ for the ${}^{6}_{\Lambda\Lambda}He$ nucleus were obtained by kinematic fitting as follows: $B_{\Lambda\Lambda} = 7.25 \pm 0.19 + 0.18 - 0.11$ MeV, and $\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.19 + 0.18 - 0.11$ MeV. This means that the ΛΛ interaction is weakly attractive. Taking into account the result of the NAGARA event, the lower limit of the mass of the H-dibaryon was determined to be 2223.7 MeV/c^2 at the 90% confidence level.

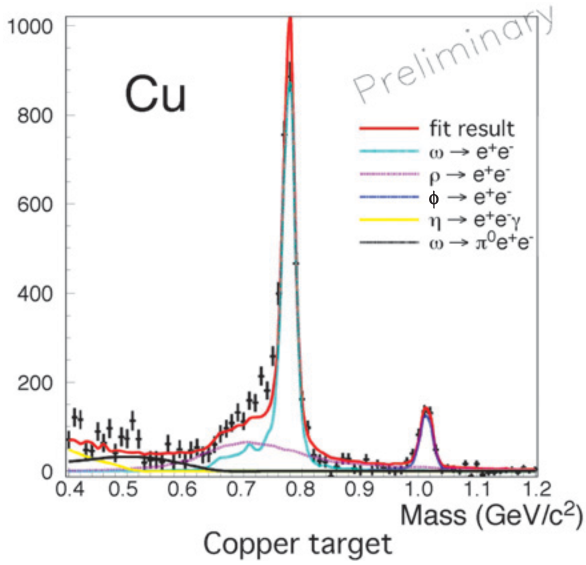

Fig. 4-2-7 Observed invariant mass spectra of e^+e^- data, after subtracting the combinatorial background, for the copper target in E325. Lines are the model calculations.

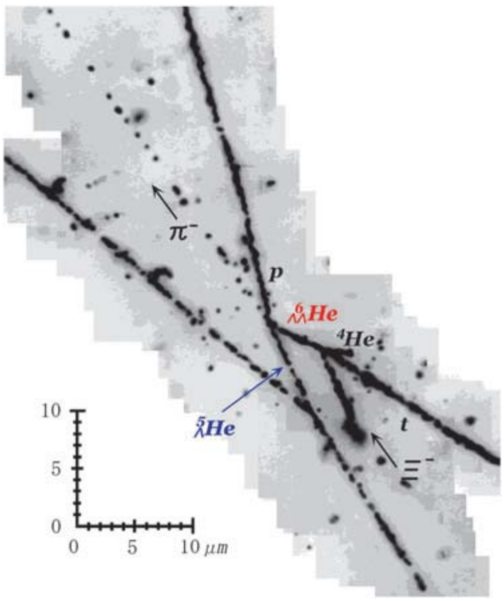

Fig. 4-2-8 NAGARA event in E373.

4.3 K2K Experiment

The KEK-to-Kamioka long-baseline neutrino oscillation experiment (K2K) is the first accelerator-based experiment with a neutrino path length extending hundreds of kilometers. The intense, nearly pure neutrino beam (98.2% ν_μ, 1.3% ν_e, and 0.5% $\overline{\nu}_\mu$), having an average $L/E_\nu \sim 200$ ($L = 250$ km, $< E_\nu > \sim 1.3$ GeV), is directed toward the Super-Kamiokande detector at Kamioka. K2K focuses on the study of the existence of neutrino oscillation in ν_μ disappearance that is observed in atmospheric neutrinos, and on the search for $\nu_\mu \rightarrow \nu_e$ oscillation, with well-understood flux and neutrino composition in the $\Delta m^2 \geq 2 \times 10^{-3}$ eV^2 region.

The K2K experiment started data taking in June 1999. On November 12, 2001, however, the Super-Kamiokande detector suffered an accident. Over a period of one year, it was rebuilt with about half of the original photomultiplier density. The rebuilt detector is called Super-Kamiokande-II, as compared to Super-Kamiokande-I before the accident. Consequently, the K2K experiment is called K2K-I and K2K-II corresponding to Super-Kamiokande-I and -II, respectively. The K2K-I experiment was formally a Japan-U.S.-Korea collaboration, with a few people joining from Poland. In the K2K-II experiment, the collaboration expanded to include members from Canada, France, Italy, Spain, Switzerland, and Russia in addition to the original members from Japan, Korea, Poland and the U.S. (see Fig. 4-3-1).

In FY2003, K2K took data from April to June and October to February. The total number of protons delivered onto the pion production target (protons on target: POT) since the start of K2K in 1999 reached 1.01×10^{20} (see Fig. 4-3-2). The net POT, successfully

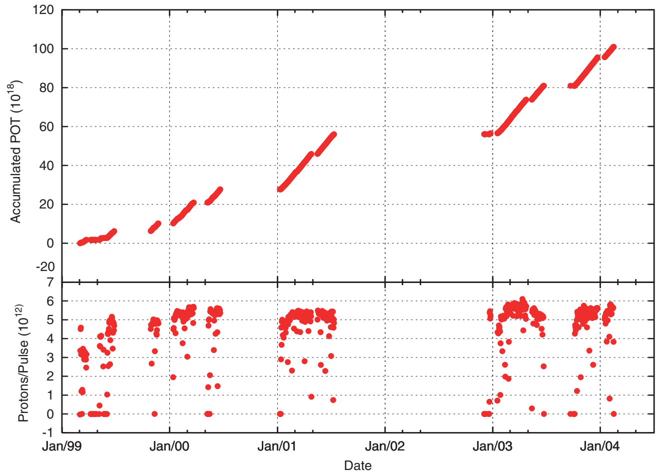

Fig. 4-3-2 History of the K2K experiment, showing accumulated POT and beam intensity per pulse.

Fig. 4-3-1 K2K-II collaboration.

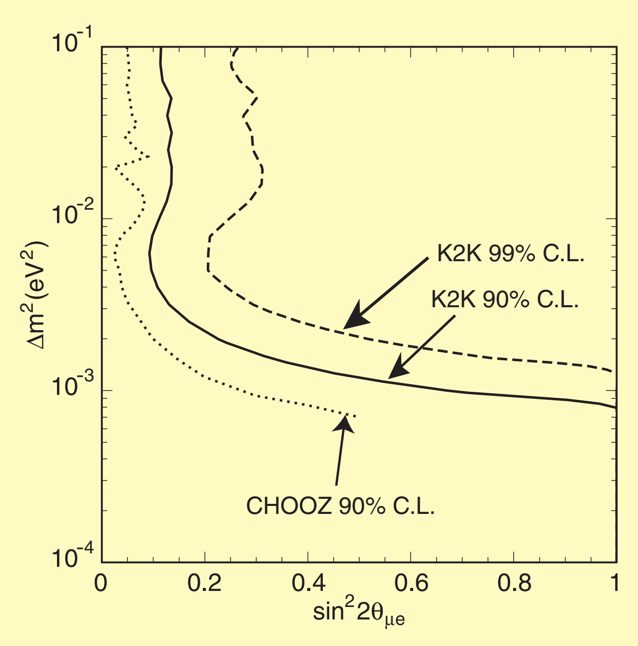

Fig. 4-3-3 Exclusion plots of $\nu_\mu \to \nu_e$ oscillations.

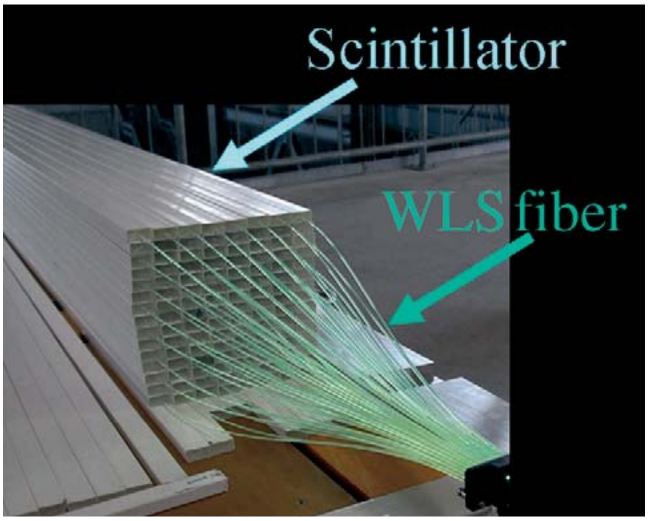

Fig. 4-3-4 Extruded scintillator strips and WLS fibers.

used for analysis of the Super-Kamiokande data, is 8.9 $\times 10^{19}$. The difference is attributable to various reasons: tuning of the beam channel, testing of the horns, Super-Kamiokande calibration, failure of Super-Kamiokande due to power failure, etc., and failure in the online data acquisition of the beam-monitoring data. As of February 2004, K2K was approaching the goal of 10^{20} net POT.

Although the main purpose of the K2K experiment is the study of ν_μ disappearance, $\nu_\mu \to \nu_e$ appearance can also be studied. Using the K2K-I data taken before the Super-Kamiokande accident, corresponding to 4.8 $\times 10^{19}$ POT, one candidate event was found. The expected background in the absence of neutrino oscillations is estimated to be 2.4 ± 0.6 events and is dominated by misidentification of events from neutral current π^0 production. The resulting confidence intervals for the $\nu_\mu \to \nu_e$ oscillations are shown in Fig. 4-3-3. This is the first accelerator long-baseline result for this oscillation mode. Assuming 3-flavor neutrino oscillations and CPT invariance, this result can be compared to the result from the CHOOZ reactor experiment. The limit on $\sin^2\theta_{13}$ by CHOOZ is converted by assuming $\sin^2\theta_{\mu e} = \frac{1}{2}\sin^2\theta_{13}$, and is also shown in Fig. 4-3-3.

A brand-new fine-grained near detector called the SciBar (Scintillator Bar) detector was installed during the summer shutdown in 2003. It is a fully active

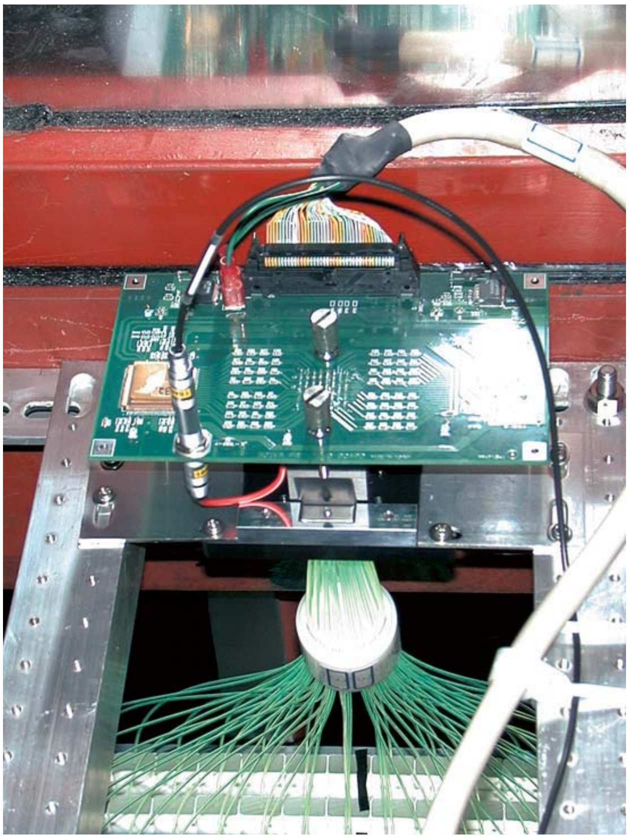

Fig. 4-3-5 This photograph shows how 64 WLS fibers are assembled in order to couple them with a 64-channel multianode PMT. A front-end electronics board is attached to the multi-anode PMT.

tracking detector consisting of 14,848 extruded scintillator strips, each 1.3 cm thick, 2.5 cm wide, and 300 cm long. A group of 116 strips are glued together to form a plane, and a combination of two planes, one horizontally and the other vertically segmented, forms a unit layer. Altogether there are 64 layers and the total scintillator volume weighs 15 tons. Each strip of scintillator is read out by a wavelength shifting (WLS) fiber, and 64 WLS fibers are coupled to a 64-channel multianode photomultiplier tube (PMT) (see Figs. 4-3-4 and 4-3-5). Figure 4-3-6 schematically illustrates the SciBar detector and the near detector complex. Figure 4-3-7 shows a sample of an interesting event observed in SciBar.

SciBar is a powerful detector to improve measurements of the neutrino energy spectrum and to study neutrino interactions around 1 GeV. As a result, SciBar will significantly contribute to improved oscillation analysis by reducing systematic errors due to uncertainties in the neutrino energy spectrum and neutrino interactions.

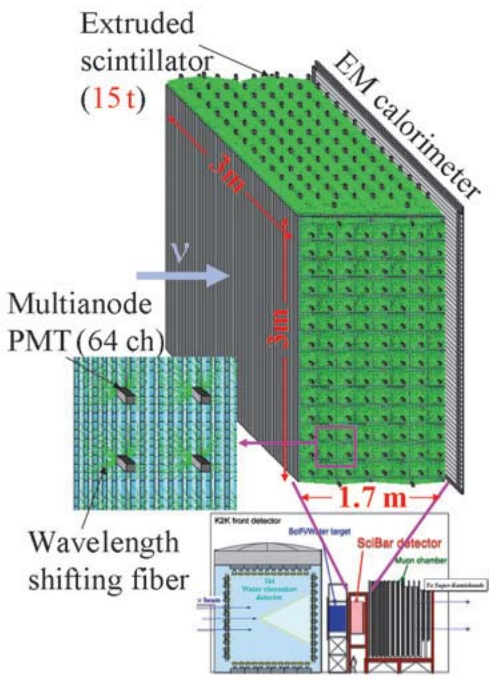

Fig. 4-3-6 Schematic illustration of the SciBar detector. Its location in the K2K-II near detector complex is also shown. The detector behind SciBar is a spaghetti calorimeter recycled from the CHORUS experiment at CERN.

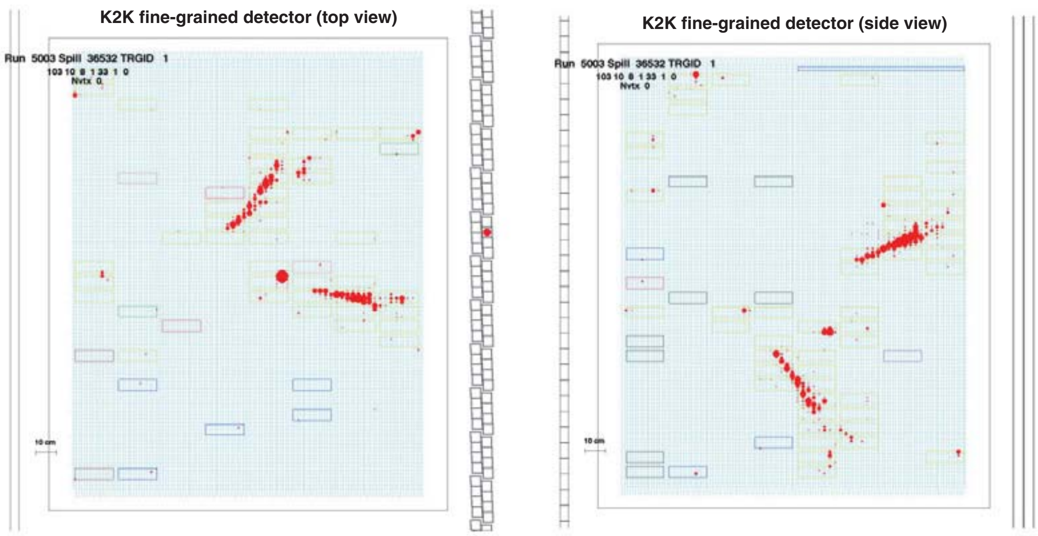

Fig. 4-3-7 A neutral-current single π^0 production event observed in the SciBar detector. The left panel shows a top view and the right panel shows a side view.