4.2 Experiments at the 12 GeV Proton Synchrotron

In FY2002, the 12 GeV Proton Synchrotron (PS) was operated in the slow beam-extraction mode from April to late December. Seven physics experiments and 19 test experiments were performed in the period. Then the accelerator was switched to the fast extraction mode for the KEK-to-Kamioka (K2K) long-baseline neutrino oscillation experiment and sent neutrinos until the end of FY2002 (March 2003) to the Super-Kamiokande detector that was finally revived after its accident in November 2001.

Experiment E391a was a physics experiment to search for the rare kaon decay $K_L^0 \to \pi^0 \nu \overline{\nu}$. This flavor changing neutral current (FCNC) process is sensitive to new physics beyond the Standard Model, and is thus one of the most interesting processes in the study of CP violation in K-meson system. The experiment is now at the stage of detector construction, in preparation for physics runs starting in February 2004. The E391a detector consists of an electromagnetic calorimeter made of pure CsI crystals, barrel veto counters made of lead-scintillator sandwich detectors, and five stages of beam counters. In FY2002, the downstream section of the detector including a part of the electromagnetic calorimeter was fabricated and tested with a neutral beam at the PS. Using the same trigger scheme and electronics, a very clean K_L mass was reconstructed (Fig. 4-2-1). Another important step in FY2002 was the fabrication of 16 front-barrel veto counter modules (Fig. 4-2-2).

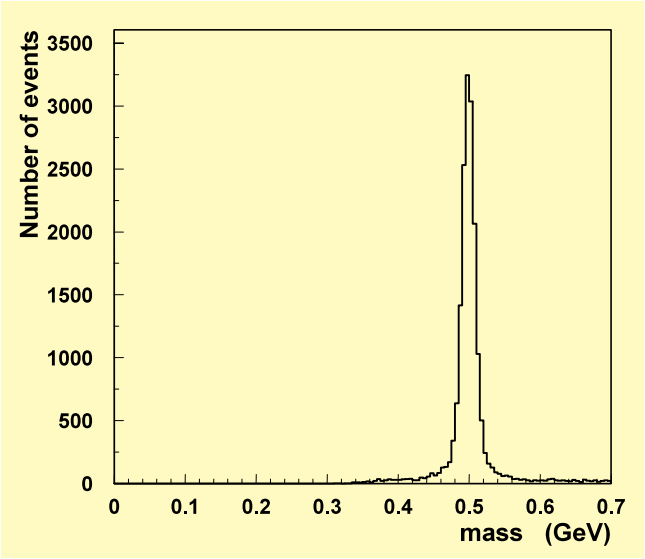

Fig. 4-2-1 The invariant-mass plot for 6 γ rays shows a very clean peak of $K_L^0 \to \pi^0\pi^0\pi^0\{K_{\pi 3}\}$ decays (E391A experiment).

The other six physics experiments are studing various effects of strange particles in nuclei: a search for the deeply bound *Kppn* state (E471), a coincidence measurement of the weak decay of ${}^{12}_{\Lambda}\mathrm{C}$ (E508), γ-ray spectroscopy of hyper fragments with stopped kaons (E509) and by the (π^+, K^+) reaction (E518), a study of the production of neutron-rich Λ hypernuclei by the (π^+, K^+) double-charge exchange reaction (E521), and a search for H-dibaryon resonance (E522). In three experiments, E508, E509, and E518, data taking was completed in FY2002.

Many of the 19 test experiments carried out in FY2002 were actually detector calibrations and detector R&D for experiments at other laboratories rather than KEK. Experiment T500/530 tested detector packages for (e, e' K^+) Λ-hypernuclei spectroscopy at the Thomas Jefferson National Accelerator Facility (Jefferson Lab). The packages were composed of water Cerenkov counters, aerogel Cerenkov counters, and a time-of-flight (TOF) counter. The water Cerenkov counters were read out by the amino-G-salt wavelength shifter and have achieved 98% detection efficiency for K^+ with 2% contamination of protons. The T512/523 group has been developing an emulsion cloud chamber for π/μ identification to reduce backgrounds in the OPERA experiment at CERN. The purpose of experiment T513 was to evaluate the performance of a neutron-insensitive photon detector that has been developed for the future KOPIO experiment at the Brookhaven National Laboratory (BNL). The T514/531

Fig. 4-2-2 Front-barrel modules fabricated for experiment E391a.

group tested aerogel threshold-Cerenkov counters to enhance particle identification capability for the PHENIX experiment at the relativistic heavy ion collider (RHIC) at BNL. One of the prototype counters achieved 99.5% detection efficiency for 2 GeV/c π with 0.5% proton contamination. The T517 group is now developing an electromagnetic calorimeter with scintillator strips for the future worldwide linear collider (Fig. 4-2-3). The group obtained the angle resolution of 54 mrad for 4 GeV showers, a good result for dense (non-gaseous) calorimeters. The T525 experiment was set up to test two types of ring imaging Cerenkov detector for the upgraded B-factory: (1) Time-Of-Propagation (TOP) counter, and (2) proximity-focusing ring-image Cerenkov counters using an aerogel radiator (Fig. 4-2-4). The T527 group measured the characteristics of the Phoswich-type NaI(Tl) counter surrounded by plastic scintillators to detect mono energetic protons up to 500 MeV. To study the pion capture process in molecules, the T529 group measured the correlation spectra of electronic and pionic X rays for various metals (Zn, Mo, Ag, Sn, and Ta) and metal oxides (Zn, Mo, and Sn). The T532 group has been developing a highresolution TOF counter by detecting Cerenkov lights from a crystal radiator using MCP-PMT. For the measured number of photo-electrons of 150–200, the time resolution of σ_t = 10.6 ps was obtained.

Some of previous experiments at the PS presented new results in FY2002. Experiment E246, which is searching for T-violating muon polarization (PT) in $K^+ \rightarrow \pi^0\mu^+\nu$ ($K_{\mu 3}$) decays, has been analyzing the data from its 1999 and 2000 runs. The analysis has been conducted in two independent ways. One of the analyses was completed in FY2002. Combining the new result with the previous results for 1996-1998 data, P_T was found to be consistent with zero: $P_T = (-1.12 \pm 2.17(stat) \pm 0.90(syst)) \times 10^{-3}$. The final result will be presented by combining this result with that obtained by the second method. The group also studied $K^+ \rightarrow \mu^+\nu\gamma$ ($K_{\mu 2\gamma}$) decay. For this decay process, the group obtained the result $P_T = (-0.57 \pm 1.85(stat) \pm 0.10(syst)) \times 10^{-2}$. Experiment E470, which recycled the detector of experiment E246 with some minor modifications, presented a new result on the direct photon emission branching ratio extracted from the decay process $K^+ \rightarrow \pi^+\pi^-\gamma$ ($K_{\pi 2\gamma}$). The branching ratio based on the 2001 data is $(6.1 \pm 2.5(stat) \pm 1.9(syst)) \times 10^{-6}$, which is consistent with the results from a stopped K^+ experiment.

Experiment E325 was carried out to study nuclear media effects appearing in the invariant mass spectra of ρ, ω, and ϕ mesons decaying into e^+e^- or K^+K^-. The experiemnt took data for about 3,200 hours over five years from 1998 to 2002. Figure 4-2-5 shows the new

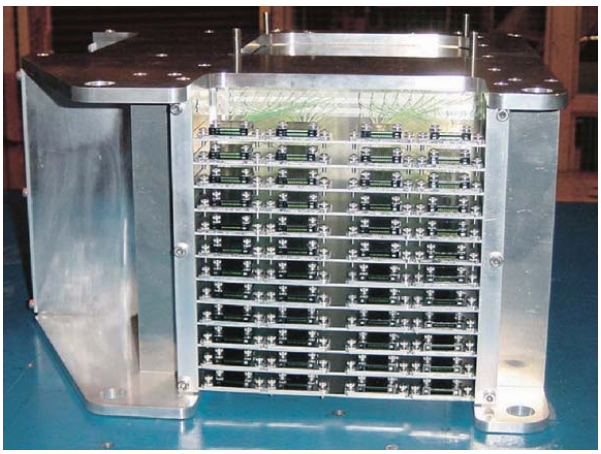

Fig. 4-2-3 R&D prototype of the electromagnetic calorimeter made of scintillator strips for experiments at the future worldwide linear colliders.

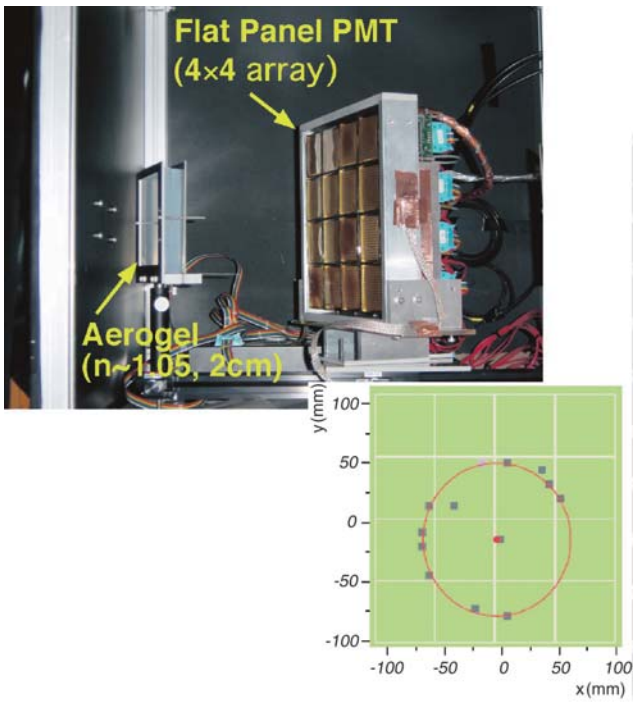

Fig. 4-2-4 The upper picture shows the test setup of an aerogel RICH detector. This is a detector study for the upgrade of the KEKB now under discussion. In the picture at lower right, 11 Cerenkov lights (black squares) observed for a particle (the red square at the center) nicely form the expected ring image (red circle).

preliminary results for the data taken in 2002. The e^+e^- invariant mass spectra after the subtraction of combinatorial backgrounds, which show clear peaks of ω and ϕ mesons, are well reproduced by vector meson decays. However, significant excess is found in the low-mass side of the ω peak and some hint of possible excess below the ϕ peak may be also seen.

Hybrid emulsion experiment E373 has been carried out to search for the hadronic states with double strangeness: double-Λ hypernuclei and the H di-baryon. About 60% of the data have been analyzed and a third candidate event was found. One possible explanation for the event topology is the sequential decay of the double-Λ hypernuclei. For all data samples, more than 10^3 Ξ^- stopping events should be found. To study hyperon-nucleon spin-orbit interactions, the E452 group measured the asymmetries of Λ and Σ^+ elastic scattering off protons. Λ and Σ^+ particles were produced through (π^+, K^+) interactions in an active liquid-scintillator target. To define the polarization axis, the Λ polarization and the left-right asymmetry of the Λp scattering were defined in the neutron rest frame of the Λ production taking into account the Fermi motion of neutrons in carbon nuclei of the target. The same definition will be applied to the Σ^+ case so as to increase statistics by adding Σ^+ hyperon events by Σ^+ production on the bound protons in the carbon nuclei to those from free protons.

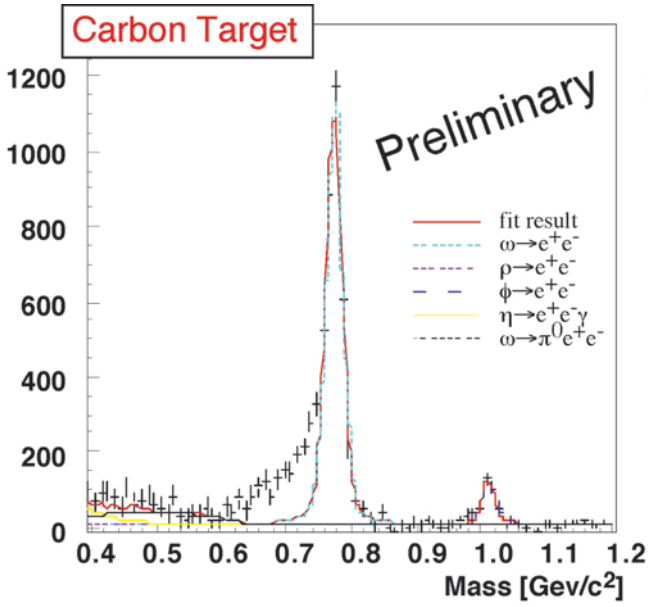

Fig. 4-2-5 The e^+e^- invariant mass spectra for the 2002 data of experiment E325A. Combinatorial backgrounds have been subtracted. Clear peaks of ω and ϕ mesons are seen together with significant excess in the low-energy side of the ω peak.

Experiment E462 is studing baryon-baryon weak interaction in nuclei by measuring the ratio Γn/Γp = Γ (Λn → nn)/Γ (Λp → np) in non-mesonic weak decay (NMWD) of ${}^{5}_{\Lambda}He$, where two-nucleon pairs, np and nn, with back-to-back angular correlation were selected. The ratio found is 0.42 ± 0.10, which is close to a recent theoretical calculation that takes into account heavier mesons. Although the result is still preliminary, the experiment has established the picture of the dominant Λp → np decay process with a significant contribution from the Λn → nn process in baryon-baryon weak interaction in nuclei.

4.3 K2K Experiment

As reported in the KEK Annual Report 2001, Super-Kamiokande (SK), the far detector of the K2K experiment, suffered from an accident on November 12, 2001, in which about 60% of the 20-inch photomultiplier tubes (PMTs) for the inner detector and 8-inch PMTs for the outer detector were destroyed.

After extensive investigation of the cause of the accident and subsequent tests of protection measures against the shock waves produced by the PMT implosion, the Super-Kamiokande and K2K collaborations started rebuilding the SK detector in April 2002. The work took about half a year to complete. The inner detector was, however, only partially rebuilt. The 20-inch PMTs then available, most of which were those PMTs that fortunately survived the accident with the remainder from the stock at the Institute of Cosmic Ray Research (ICRR), were only 47% of the 11,146 PMTs necessary to cover the whole inner wall of the large water tank of the SK detector. In the restoration, all PMTs were encased in plastic covers as shown in Fig. 4-3-1. The front panel of the PMT case is made of 12 mm-thick UV-transparent acrylic so that, even if one PMT might implode due to water pressure, the shock waves should be safely confined in its plastic case. Although the inner detector still suffers from the accident, the outer detector has been completely restored thanks to the support of the U.S. Department of Energy.

Fig. 4-3-1 An encased 20-inch PMT for the Super-Kamiokande-II detector.

The Super-Kamiokande experiments before and after the accident are now called Super-Kamiokande-I (SK-I) and Super-Kamiokande-II (SK-II), respectively. Similarly, we refer to the K2K experiment with the SK-II detector as K2K-II and the one before the accident as K2K-I. While K2K-I was essentially a Japan-US-Korea collaboration with a few members from Poland, K2K-II enjoys a larger collaboration including members from France, Italy, Spain, Switzerland, Russia, and more recently from Canada.

Filling of the SK-II detector with water started at the beginning of October 2002, and K2K-II started data taking at the end of December 2002. After the New Year holidays in 2003, data taking resumed on January 18, 2003. Figure 4-3-2 shows the status of the K2K-II experiment around the end of April 2003. The total number of protons delivered onto the pion production target (protons on target: POT) for the K2K-II experiment has reached to 1.7×10^{19}. The corresponding SK-II live time was about 1.5×10^{19} POT.

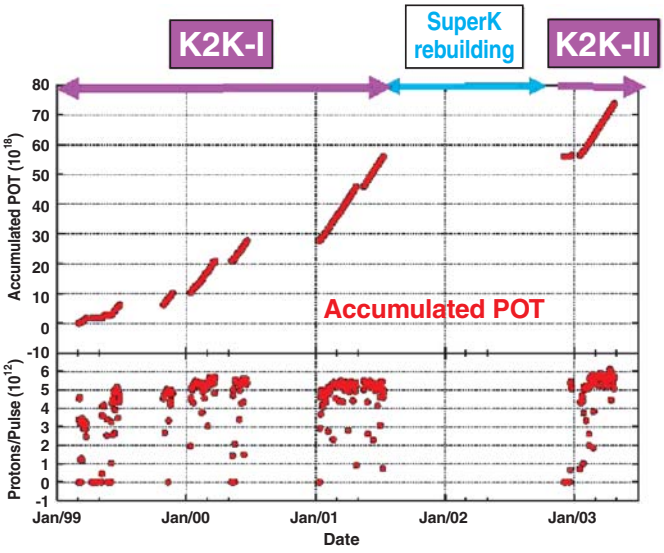

Fig. 4-3-2 Status of the K2K experiment. The integrated number of protons delivered onto the target (POT) and beam intensity per pulse are shown.

The K2K-I results for neutrino oscillations were published in January 2003. As already described in the 2001 Annual Report, 56 neutrinos from the KEK 12 GeV Proton Synchrotron (PS) were observed inside the SK-I fiducial volume of 22,500 tons of water. Assuming no oscillation, we expect $80.1^{+6.2}_{-5.4}$ events based on the neutrino intensity measured in the 1,000-ton water Cerenkov detector located at the KEK site.

Figure 4-3-3 shows the E_ν spectrum for 29 fully contained 1-ring μ-like events observed in the SK-I fiducial volume. In the event reconstruction, the kinematics of a two-body quasi-elastic (QE) reaction were assumed. The observed energy spectrum, therefore, mostly consists of that from real muon neutrinos or that of non-QE background. The non-QE background was estimated by a Monte Carlo simulation for the neutrino interactions with proper detector response. The box histogram is the expected spectrum without oscillations, where the height of boxes indicates the systematic error. The solid line is the best-fit to the data with $\sin^2 2\theta = 1.0$ and $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2. The histograms are normalized to 29 observed events. The dashed line shows the expected spectrum with no oscillations, which is normalized to the expected number of events (44). The probability that the present observation is due to statistical fluctuation rather than neutrino oscillation is less than 1%.

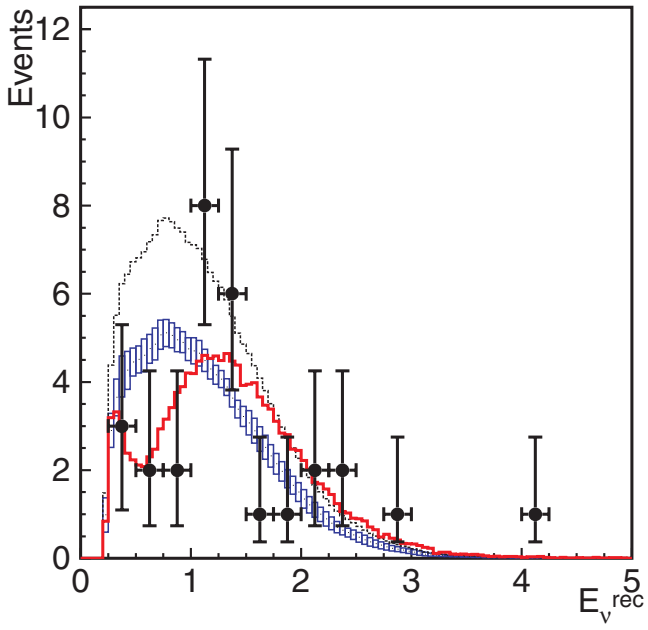

Fig. 4-3-3 The neutrino spectrum observed at the SK-1 detector compared with the spectrum expected for no oscillation and that for oscillation of best-fit.

Figure 4-3-4 shows the allowed regions of the oscillation parameters. The dashed, solid, and dot-dashed lines are the 68.4%, 90%, and 99% confidence level contours, respectively. The best-fit is marked by the star. The measured oscillation parameters are consistent with those suggested by the atmospheric neutrino observations in SK-I.

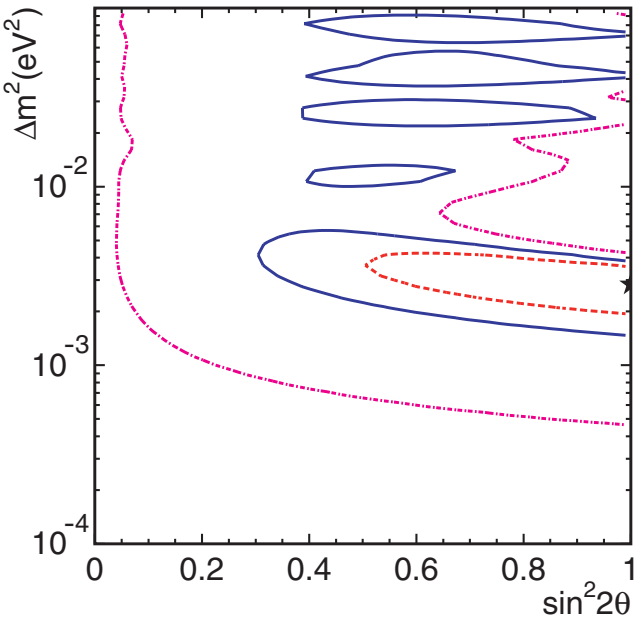

Fig. 4-3-4 Allowed regions of the oscillation parameters.