4.2 Experiments at the 12 GeV Proton Synchrotron

In FY2000, the KEK 12 GeV Proton Synchrotron (KEK PS) was in operation altogether for 7.5 months: 3.5 months in the slow beam-extraction mode and 4 months in the fast beam-extraction mode, providing a neutrino beam for the K2K (E362) long-baseline neutrino oscillation experiment. During the periods in slow beam-extraction mode, seven experiments were performed. Data taking is now complete for four of them: E246, E373, E443 and E462.

At the K5 beam line of the KEK PS, Experiment E246 searched for a time-reversal violation (T-violation) effect in transverse muon polarization of the charged kaon decay $K^+ \to \pi^0\mu^+\nu$. The experiment used a superconducting toroidal spectrometer. Final data taking for the experiment was completed in FY2000, increasing the total statistics by 25%. Analysis of the data taken in 1998 was continued while adopting two independent methods. New results obtained for combined 1996-1997 and 1998 data are again consistent with no T-violation with a statistical accuracy of $\Delta \mathrm{Im}\xi = 0.0175$. The systematic error is estimated to be about one-sixth of the statistical error. The 1999-2000 data is now being analyzed. As a physics byproduct, the experiment has also measured the form factors of $K^+ \to \pi^0 e^+ \nu$ decay. The result shows no evidence for tensor or scalar couplings in contradiction to current world averages.

The partial restoration of chiral symmetry in dense matter predicts the in-medium modification of vector mesons. At the EPA-B beam line of the KEK PS, Experiment E325 aims to detect the effect by measuring the invariant masses of the vector mesons produced in 12 GeV proton-nucleus interactions. Both the $e^+ e^-$ decays and the $K^+ K^-$ decays of the vector mesons are measured using the same apparatus. The $e^+ e^-$ mass spectrum taken in 1998 with a Cu target shows a broader ω peak as is seen in Fig. 4-2-1. Although the theoretical interpretation of the data is not yet conclusive, it is consistent with the prediction. This was the first observation of leptonic decay of vector mesons in normal nuclear matter. Data from the 1999 and 2000 runs are now being analyzed and the next data taking is scheduled in 2001.

The study of the double strangeness system is important for the unified description of baryon-baryon interactions in $SU(3)_f$ symmetry. The E373 Hybrid

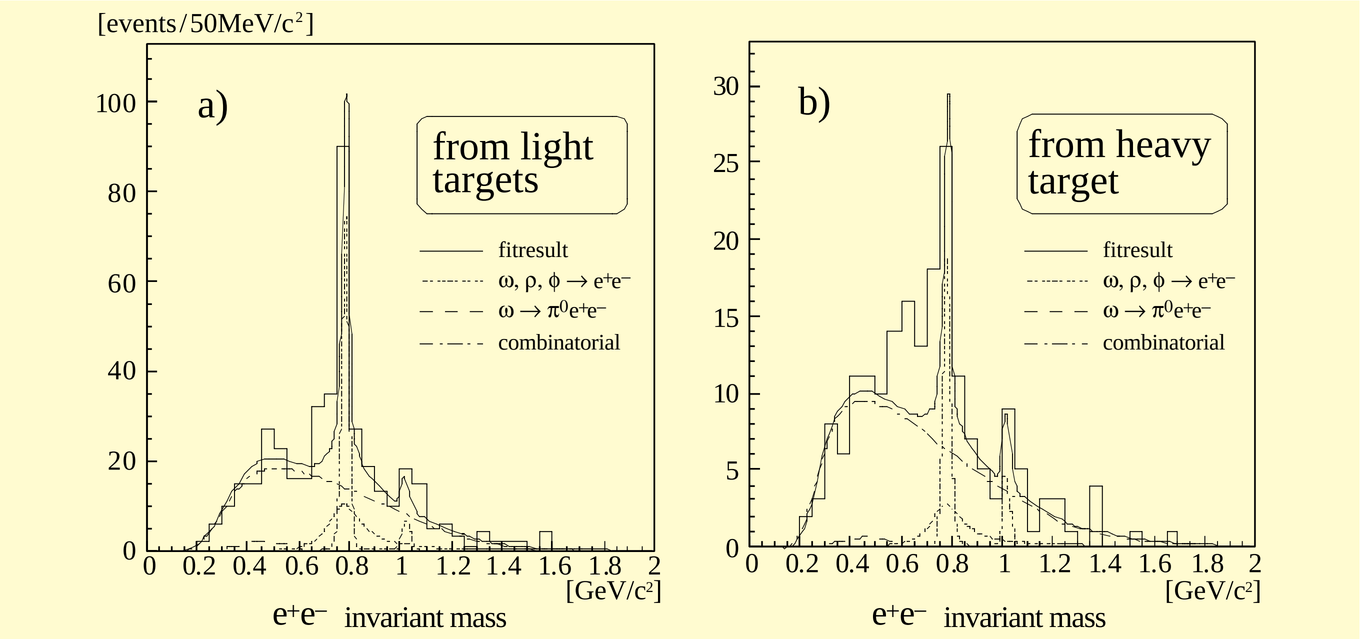

Fig. 4-2-1 Invariant mass spectra of e^+e^- pairs: a) for the light nuclear targets (C and CH_2) and b) for the heavy nuclear target (Cu). The solid lines show the best fits obtained as a cocktail of known hadronic sources with a combinatorial background. The dotted lines indicate the contributions from ρ, ω, and ϕ decays and the dashed lines the contributions from $\omega \to \pi^0 e^+ e^-$ decays. The combinatorial background is given as the dot-dashed lines. A clear excess of events in the mass region below the ω meson peak is seen.

Emulsions Experiment searches for S=–2 nuclei by collecting Ξ^--hyperon stopping events with a probability of ten times higher than that seen in the previous experiment, E176. Having analyzed about 10% of the data, the group has found one event with twin single-Λ hypernuclei and two events with a double-Λ hypernucleus. The twin single-Λ hypernuclei event is uniquely identified as $\Xi^- + {}^{14}N \rightarrow {}^{5}_{\Lambda}He + {}^{5}_{\Lambda}He + {}^{4}He + n$. The first double-$\Lambda$ hypernucleus event is interpreted as $\Xi^- + {}^{12}C \rightarrow {}^{10}_{\Lambda\Lambda}Be$ $(or\ {}^{10}_{\Lambda\Lambda}Be^*) + t$, assuming that the two-body reaction occurs in the $\Xi^- + {}^{12}C$ system. The second double-Λ hypernucleus event, shown in Fig. 4-2-2, has a clean topology where the hypernuclei and their decay have been uniquely identified as $\Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$; ${}^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + \pi^- + p$; ${}^{5}_{\Lambda}He \rightarrow p + d + 2n$. Preliminary analysis of the ${}^{6}_{\Lambda\Lambda}He$ nuclei by the group has established the attractive Λ-Λ interaction with $\Delta B_{\Lambda\Lambda} \sim 1$ MeV, where the error is estimated to be less than 0.5 MeV. This $\Delta B_{\Lambda\Lambda}$ value is significantly smaller than in previous estimates, and gives a new lower dibaryon mass limit of ~ 2224 MeV/c^2 (90% confidence level).

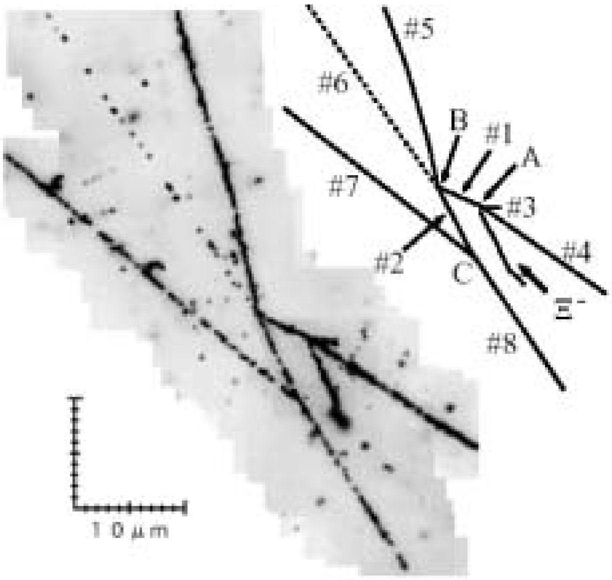

Fig. 4-2-2 Emulsion image of the double-Λ hypernucleus ${}^{6}_{\Lambda\Lambda}He$ event measured by the experiment E373. A Ξ^- hyperon was captured by ^{12}C in the emulsion at Point A. Particle track #1, produced together with the stable nuclei #3 and #5 in the capture process, decays into #2, #5 and #6 tracks at Point B. Particle #2 then decays into two tracks #7 and #8 and one or more neutral particles. Tracks #5 and #7 stop in the emulsion. Track #6 is identified as a π meson by the topology of the track. Although Track #7 escapes from the emulsion, its energy is measured in the scintillation fiber block that follows the emulsion. The ranges of the double-Λ hypernucleus (track #1) and the single-Λ hypernucleus (track #2) are 8.3 and 9.2 μm, respectively.

The E391 searches for $K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ rare decay. One of the key issues in the success of the experiment is the construction of a new pencil K^0 beam. The beam line was completed in March 2000 at the EP2-C beam channel of the KEK PS. It consists of six stages of collimators, a pair of bending magnets and a vacuum system, as shown in Fig. 4-2-3. In April and December 2000, beam surveys were performed to measure the background neutrons and photons (Fig. 4-2-4). The beam collimation system was found to be very effective in providing a beam tail at a level of 10^{-4}, the best achieved collimation of GeV neutral beams so far. The experiment plans to use a lead/scintillator sampling detector as the barrel γ veto detector. This year, a 1 m-long prototype detector (Fig. 4-2-5) consisting of 86 lead/scintillator (1 mm/5 mm) layers was tested in Test Experiment T466. The energy resolution measured for

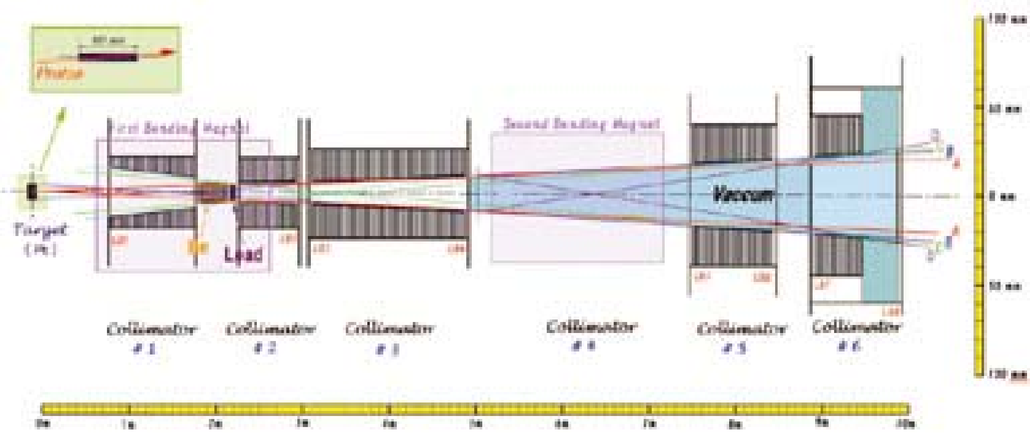

Fig. 4-2-3 New K^0 beam line for Experiment E391a.

electrons was σ/E = 5.3%/$E(GeV)$ including the beam momentum spread, and the photoelectron yield is N_{pe} = 5.7/MeV. The uniformity of the detector response and the light attenuation in the Wave-Length-Shifting (WLS) fibers were also studied with hadron beams. Extrapolating these results, the number of photoelectrons in the 5.5 m module designed for the E391 experiment is estimated to be N_{pe} = 7–8/MeV. This photoelectron yield is large enough to veto photon backgrounds effectively. A prototype CsI calorimeter for the experiment was also tested in Experiment T473.

Experiment E393 explored the thermodynamic nature of highly excited nuclear matter produced in GeV-energy nuclear reactions. Looking for possible density effects in the Target Multi-Fragmentation (TMF) reaction, the group is measuring the inclusive energy spectra of fragments in 8 and 12 GeV proton interactions with heavy nuclear targets at KEK PS and comparing with them those acquired from 8 and 12 GeV light-ion beams. The ion beam data are taken at the National Institute of Radiological Sciences (NIRS) in Chiba. The fragments with masses of 3 ~ 30 produced by the 8 GeV ^{16}O and ^{20}N ion beams show Maxwell-Boltzmann-type distributions, as in the case of the TMF reactions with 8 GeV protons, but their cross sections are 4–5 times larger and their Coulomb peaks are much broader.

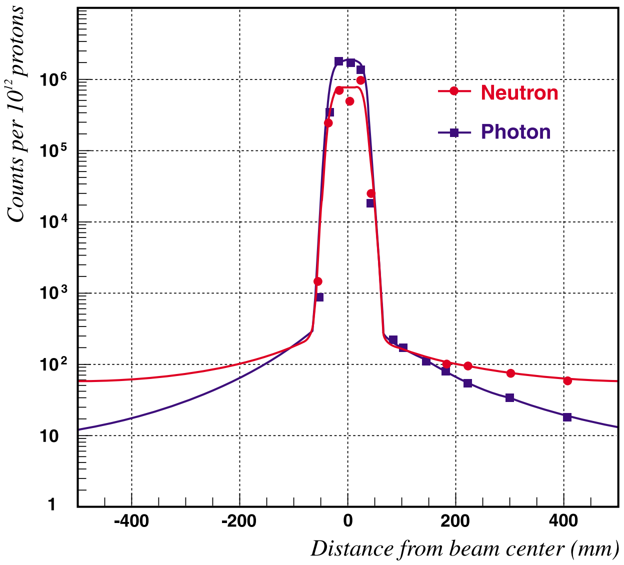

Fig. 4-2-4 Profiles of neutrons and photons measured at the new K^0 beam line.

Fig. 4-2-5 Side view of a 1 m-long prototype of the barrel γ veto detector for Experiment E391a.

The E438 group studies the Σ-nucleus optical potential by measuring the (π^-, K^+) -inclusive spectra with different nuclear targets: C, Si, Ni, In, and Bi. Figure 4-2-6 shows the spectra measured for the Si target, together with calculations in the DWIA framework with three different Σ-nucleus potentials. A significant number of events seen in the bound region (B_Σ > 0) imply that a finite strength of the Σ-nucleus potential exists. Neither the "shallow" potential nor the "atom-DD" potential reproduce this measurement. The latter potential was derived from the analysis of Σ^--atom X-rays and has a strong repulsive core. The data, however, seems to indicate a much stronger repulsive core. The present result provides important information for the study of hyperon-nucleon interactions as well as for understanding the role of hyperons in dense matter such as neutron stars.

The E443 experiment measures the neutron spallation induced by protons in order to improve the calculation codes based on the intra-nuclear-cascade evaporation model. These codes, such as NMTC and HETC, are often used in designing spallation neutron sources and accelerator-driven subcritical reactors for nuclear waste transmutation and energy production. The experiment was carried out at the π2 beam line at the KEK-PS. It measured neutrons produced at 0° and 5° in 0.8 and 1.5 GeV proton interactions with Fe and Pb targets. Neutrons were detected in two detectors filled with an NE213 liquid organic scintillator. Their energy was measured by the time-of-flight technique.

In this fiscal year, the hyperon-nucleon scattering Experiment E452 has started at the K2 beam line. The experiment is the followup to the previous two experiments (E251, E289). The purpose of the present experiment is to study the spin-dependent hyperon-nucleon

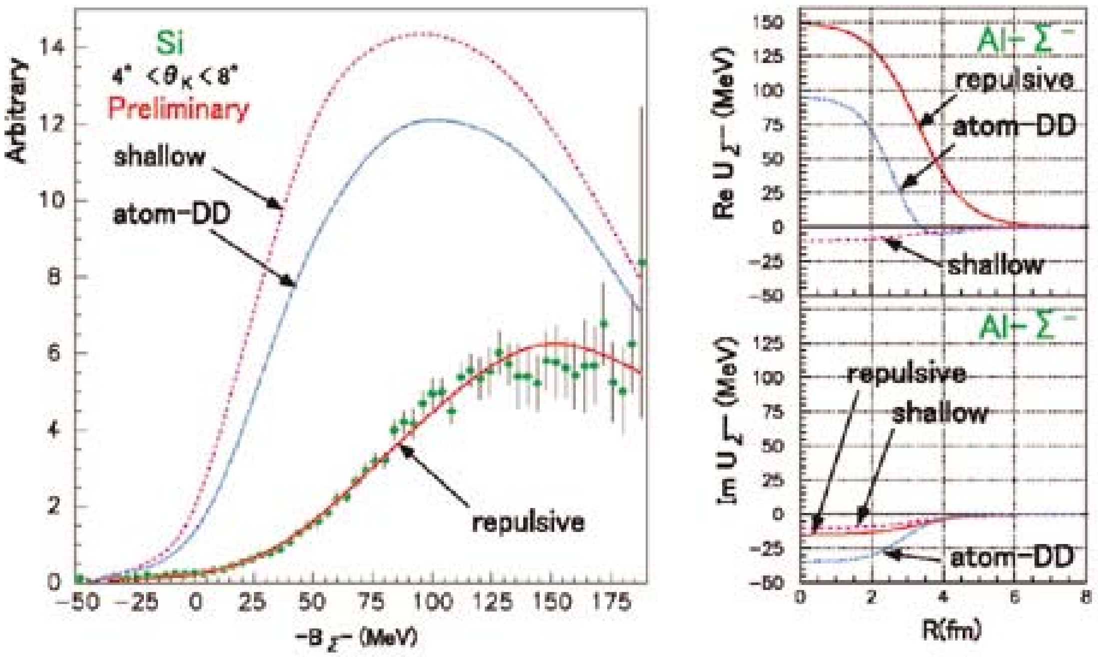

Fig. 4-2-6 (π^-, K^-) inclusive spectra measured for an Si target in Experiment E438. Shown together are predictions in the DWIA framework with three different Σ-nucleus potentials (left). The real (upper) and imaginary (lower) parts of these potentials are also shown (right).

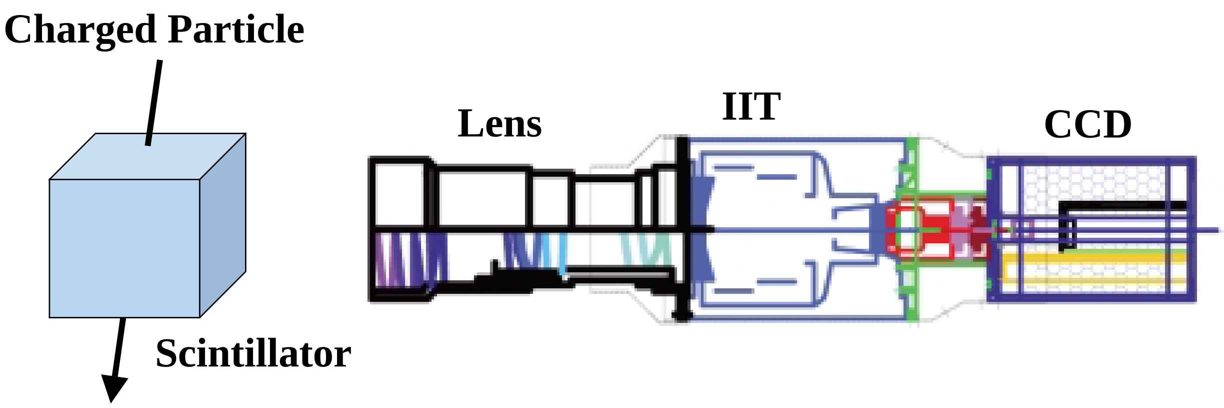

Fig. 4-2-7 New SCITIC (SCIntillating Track Image Camera) track detector developed by the E452 group.

interaction; in particular, to determine the spin-orbit coupling of the Σ^+p interaction by measuring the left-right asymmetry of the polarized-Σ^+ scatterings. The polarized hyperons were produced via (π^+, K^+) reactions in a liquid scintillator active target. The group has developed a new-type of tracking detector, the SCIntillating Track Image Camera (SCITIC) to record pictorial data of the hyperon scatterings with a fast trigger signal (Fig. 4-2-7). Test data were taken to check the performance of SCITIC together with a fast pictorial-data acquisition system. Kaons in the production angles from 20^0 to 40^0 in 1.6 GeV/c pion interactions were selected for large Σ^+ polarization. Approximately 60,000 pictures were taken during the test runs, of which about 500 pictures are expected to record Σ^+ hyperon scatterings. Data analysis is currently under way with a new computer-assisted scanning algorithm. The next data taking is scheduled for fall 2001 with a new lens system for SCITIC.

The E462 group studies the Non-Mesonic Weak Decays (NMWD) of Λ hypernuclei to gain an understanding of the weak decay process in nuclear matter. One of the immediate goals of the experiment is to determine the ratio of the two decay widths $\Gamma(\Lambda p \rightarrow$

$np)/(\Gamma(\Lambda n \to nn)$ by measuring the nucleon pairs, both $n + p$ or $n + n$, from ${}^{5}_{\Lambda}He$, the lightest "spin-isospin saturated" Λ hypernucleus. The large ratios reported by recent experiments have been one of the puzzles in the NMWD study. If the ${}^{5}He$ NWMD is dominated by the two-body decay process $\Lambda + N \to N + N$, which is possible only in nuclear matter, the two decay nucleons have a strong back-to-back correlation and the sum of their energies peaks at a Q-value of approximately 150 MeV. By detecting such nucleon pairs, it should be possible to determine precisely the ratio of the decay widths. So far this year, about 20,000 ${}^{5}He$ events have been accumulated. The measured spectrum of the decay neutrons, although preliminary, does not show any peaks around 76 MeV, half of the Q-value, as seen in Fig. 4-2-8. This result suggests a significant contribution from the two-nucleon induced decay $\Lambda + N + N \to N + N + N$. The experiment will be continued next year to improve the statistics by a factor three or more.

In FY2000, twenty test experiments were carried out for detector calibrations and detector R&D. The purpose of Experiment T467 was to check the performance of the thin gap chambers for the ATLAS end-cap muon trigger system. Mass production of the chambers is now starting at KEK. For the design of the central tracking detector at the Japan Linear Collider (JLC), the T469 experiment performed dE/dx measurements with a gas mixture of CO_2 (90%)/isobutane (10%). The measurements were made using a small jet chamber with 10 sampling wires. The T472 group brought a new position sensor, a β-selection type Cerenkov counter (POSCH) for η- and ω-mesoic nuclear search (S214) at GSI. The background rejection by POSCH was confirmed to be better than 10^{-3} over the wide incident angles of ± 60 mrad, with ${}^{3}He$ detection efficiencies of more than 98%. The position resolution for ${}^{3}He$ was estimated to be $\sigma \sim 2$ mm. The T475 group, which proposes an experiment to study the Gerasimov & Drell-Hearn (GDH) sum rule at Spring-8, tested a prototype gas Cerenkov counter with atmospheric CO_2 gas (n = 1.00041). The T476 experiment was to study basic performance of a fine-segmented liquid scintillator detector with wave-length-shifting (WLS) fiber readout (Fig. 4-2-9). The detector is one of the candidates for neutrino detection in the upgraded K2K experiment. Experiments T465 and T480 focus on the study of the pionic hydrogen atoms by measuring the pion capture process in the liquid and gas phases. The chemists doing the experiment are now designing an experiment to measure the Auger electrons emitted during the initial step of pion capture and the electronic X-rays (eX-rays) in coincidence with the pionic X-rays (πX-rays).

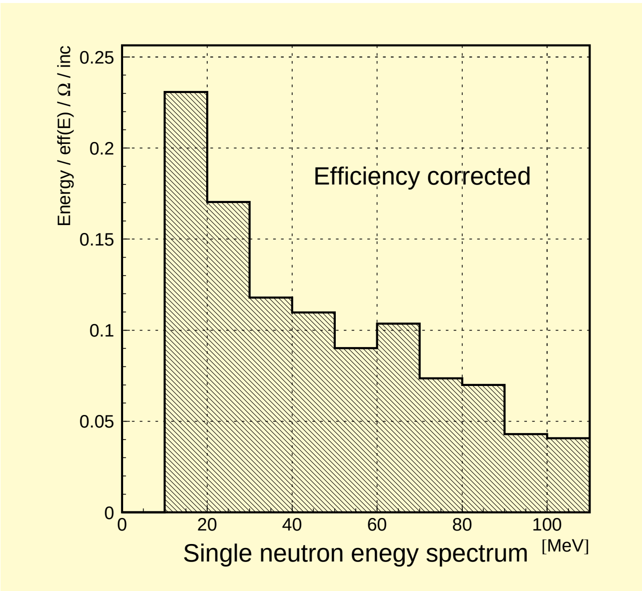

Fig. 4-2-8 Energy spectrum of neutrons from ${}^{5}_{\Lambda}He$ decays. No peak at Q-value/2 ~ 76 MeV is seen, suggesting a significant contribution from the two-nucleon induced non-mesonic decays $\Lambda + N + N \to N + N + N$.

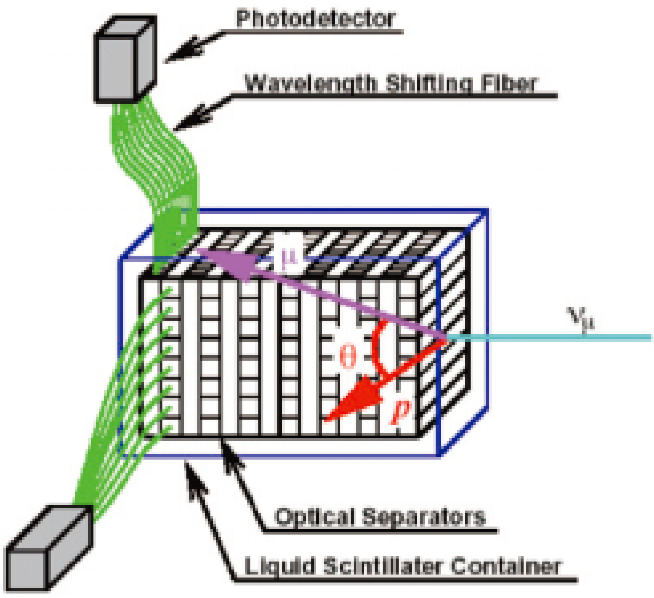

Fig. 4-2-9 Schematic view of the fine-segmented liquid scintillator detector with wave-length-shifting (WLS) fiber readout; one of the candidates for the neutrino detector in upgrading the near detector system of the K2K experiment.

4.3 K2K Experiment

The K2K (KEK-to-Kamioka) experiment is the first long-baseline neutrino oscillation experiment to be performed by an international collaboration between physicists from Japan, Korea and the USA. An almost pure muon neutrino beam (98.2% ν_μ, 1.3% ν_e and 0.5% $\overline{\nu}_\mu$) is produced at the KEK 12 GeV PS and sent over 250 km to the Super-Kamiokande (SK) detector at Kamioka, Gifu prefecture, operated by the University of Tokyo. The SK 50,000-ton water Cerenkov detector observes the neutrino interactions generated by the KEK neutrino beam. The experiment focuses on the existence of neutrino oscillation in the ν_μ disappearance mode, which was first reported by the SK collaboration after a careful study of the deficit in the atmospheric muon neutrinos. The experiment also searches $\nu_\mu \rightarrow \nu_e$ oscillations in the $\Delta m^2 \geq 2 \times 10^{-3} eV^2$ region.

On June 19, 1999, the SK detector recorded the first neutrino event originating from the KEK neutrino beam. In fiscal year 1999, the experiment observed 17 neutrino events in its 22,500-ton volume, while approximately 29 events were expected to occur when the neutrino does not oscillate. Considering both the statistical and systematic errors in the measurements, it was then concluded that the null oscillation result was disfavored at the 95% confidence level.

The experiment continued to run during the year 2000 and had observed 28 events by the end of June 2000. All the events coincided with the expected arrival time of the neutrino beam as calculated from the beam spill time (1.1 μsec) and the time of light over 250 km, thus are safely identified as neutrino events originated by the KEK neutrino beam. When no oscillation occurs, the expected number of events is $37.8^{+3.5}_{-3.8}$, which is derived from the number of neutrino interac-

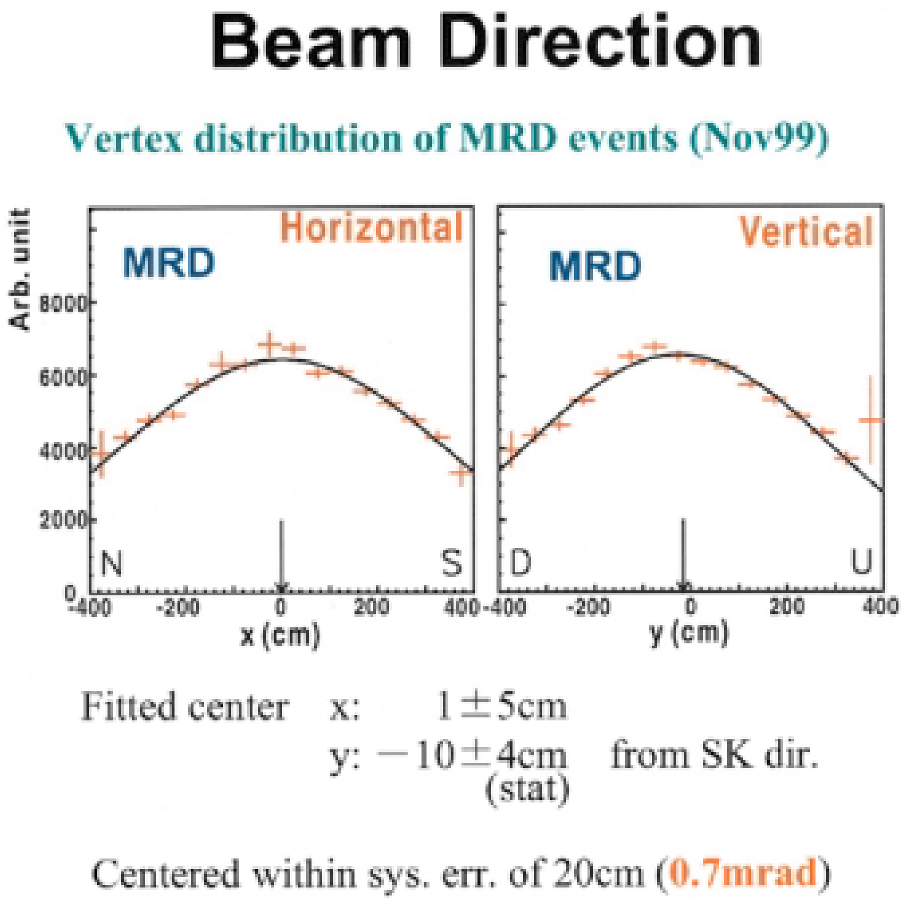

Fig. 4-3-1 Horizontal and vertical profiles of the ν_μ beam measured by the muon range detector in November 1999. The curves are predictions computed from simulations. The arrow shows the direction of Super-Kamiokande.

tions measured in the 1000-ton water Cerenkov detector of the near detector system. The near detector system is located 300 m downstream of the production target. The background from atmospheric neutrinos is estimated to be around 10^{-3} events for the current data sample.

The characteristics and stability of a neutrino beam are vital for the K2K experiment. In particular, the neutrino beam must be pointed precisely at the SK detector. The profile of the neutrino beam is monitored by a muon range detector at the near-detector system measuring the muon neutrino interactions with iron. Figure 4-3-1 shows the measured profile together with the simulation result. As seen in the Figure, the beam is exactly centered on the SK detector. In Fig. 4-3-2, the center of the beam profile is plotted as a function of time. It can be seen that the neutrino direction was stable within ± 1 mrad throughout this running period. Because the calculated neutrino spectrum at 250 km is almost constant over nearly 1 km, the required precision of the beam pointing is 3 mrad. The measured pointing accuracy, therefore, assures the stable delivery of the KEK neutrino beam to the SK detector.

From January to March, 2001, more data were taken without any serious problems. The experiment will continue to run until July, 2001. It is expected that the statistical measurements will be doubled by this time.

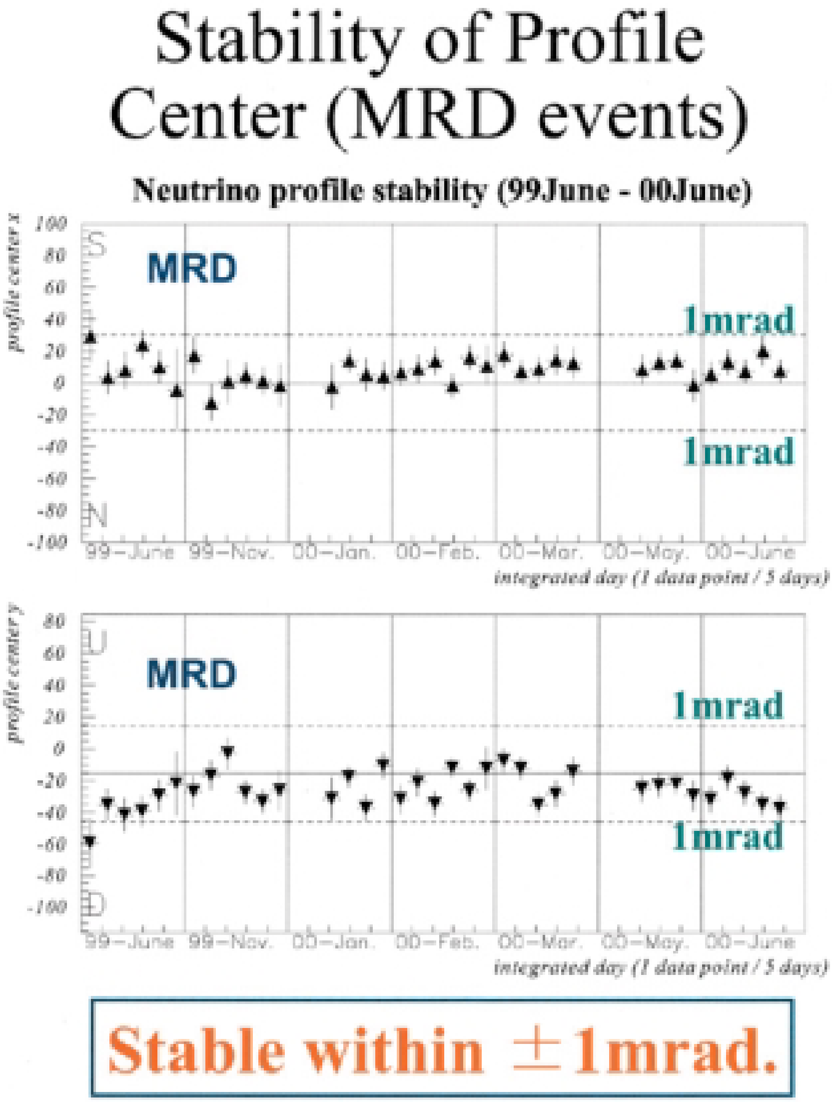

Fig. 4-3-2 The pointing stability of the KEK neutrino beam. The fitted centers of the horizontal and the vertical profile are plotted over five-day periods. The dashed lines show directions ± 1 mrad to the Super-Kamiokande detector.