Neutrino Interaction Measurement in K2K-SciBar

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Abstract

SciBar is a fully-active scintillator detector, which was newly installed in the near site detector complex of the KEK to Kamioka long baseline neutrino oscillation experiment. The main purposes of SciBar are to improve the measurement of neutrino energy spectrum shape and neutrino-nucleus interaction, which are necessary input for the neutrino oscillation study. In this article, the status of the neutrino interaction study with SciBar is presented.

1. Introduction

The KEK to Kamioka long baseline neutrino oscillation experiment (K2K) is the first accelerator-based long-baseline neutrino oscillation experiment [1]. A wide-band neutrino beam with a mean energy of 1.3 GeV is produced by the KEK 12GeV PS and aimed towards Super-Kamiokande (SK), located 250 km west from KEK. In K2K, the signatures of neutrino oscillation appear as a distortion of the neutrino energy spectrum shape and a deficit in the total number of events at SK. The expectations for these are derived based on measurements at the near-site detectors located 300 m downstream from the proton beam target. The neutrino energy spectrum is measured using charged current quasi-elastic (CCQE) scattering ($\nu_\mu + n \rightarrow \mu + p$), which is a dominant process around 1 GeV. The latest result from K2K [2] shows evidence for the disappearance of muon neutrinos and is consistent with the atmospheric neutrino results. From those results, the neutrino energy of the oscillation maximum is expected to be around 0.6 GeV for K2K. Thus, more precise measurement of neutrino spectrum shape and precise estimation of the amount of background from non-QE interaction in the SK data below 1 GeV are vital to improve the accuracy of the oscillation measurement. To improve the determination of the neutrino energy spectrum shape and to understand neutrino interaction with nuclei, a fully-active scintillator detector, named SciBar (scintillator bars) [3], was installed in August 2003. In this article, status of the neutrino interaction study in the energy region of sub-GeV to a few

pp. 143–153

GeV with SciBar is presented.

2. SciBar Detector

The SciBar detector consists of 14,848 extruded plastic scintillator strips read out by wavelength-shifting fibers and 64 channels multi-anode PMTs. A schematic drawing of SciBar is shown in Figure 1. Scintillator strips with dimensions of $1.3 \times 2.5 \times 300$ cm^3 are arranged in 64 layers. Each layer consists of two planes to measure horizontal and vertical position. The scintillator also acts as the neutrino interaction target; it is a fully active detector and has high efficiency for low momentum particles. The size of the detector is $300 \times 300 \times 170$ cm^3 providing total mass of 15 tons, while a volume of $260 \times 260 \times 135.2$ cm^3 (9.38 tons) is used as a fiducial volume in analysis. Due to the fine segmentation, the minimum reconstructable track length is 8cm, which corresponds to 450 MeV/c for a proton and 100MeV/c for a muon, respectively. A track finding efficiency of more than 99% is achieved for a single track with a track length of more than 10 cm. The track finding efficiency for a second, shorter track is lower than that for the single track due to overlap with the first track. This efficiency increases with second track length and reaches 90% at a track length of 30 cm. In SciBar, the particle identification is performed based on dE/dx information. The particle identification capability is verified using cosmic ray muons and the second tracks in the QE sample, where the latter provides a proton sample with a purity of more than 90%. The probability to mis-identify a muon track as proton-like is 1.7% with a corresponding proton selection efficiency of 90%.

An electro-magnetic calorimeter (EC) was installed behind of the scintillator part to measure ν_e contamination in the beam and π^0 yield from neutrino-interactions. EC is comprised of 2 planes of 30 horizontal and 32 vertical modules re-used from the CHORUS experiment [4]. The module is made of lead sheets and scintillating fibers. It has a dimension of $4 \times 8 \times 262$ cm^3, and consists of two of 4×4 cm^2 cells. EC has 11 radiation length along the beam axis and covers 2.6×2.6 m^2. The energy resolution is $14/\sqrt{E\ (\mathrm{GeV})}$ %.

The SciBar has been operated stably since October 2003 and we collected data corresponding to $1.7{\times}10^{19}$ protons on target with SciBar. An event display of a typical CCQE event candidate is shown in Figure 2.

3. Neutrino interaction simulation in SciBar - NEUT

The NEUT Monte Carlo (MC) simulation program library [5] is used to simulate the neutrino interactions with the nucleus. The Lewellyn Smith model [6] and the Rein and Sehgal model [7] are employed for quasi-elastic (QE)

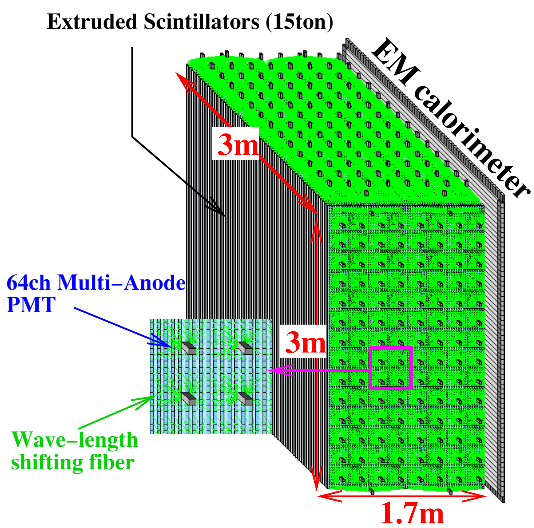

Fig 1. A schematic drawing of SciBar. Extruded scintillator strips are arranged vertically and horizontally. The size of scintillator part is $3 \times 3 \times 1.7\text{m}^3$ and the weight is about 15 tons.

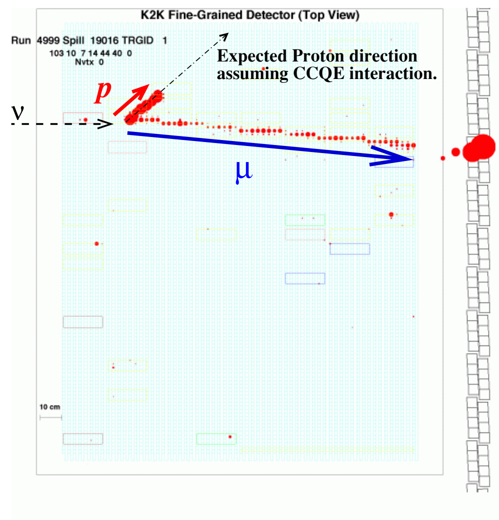

Fig 2. An event display of typical CCQE event. In the display, each hit is shown as a closed circle, whose area is proportional to dE/dx. One track extends to Muon range detector is muon and the other track which shows larger energy deposition than minimum ionizing particles.

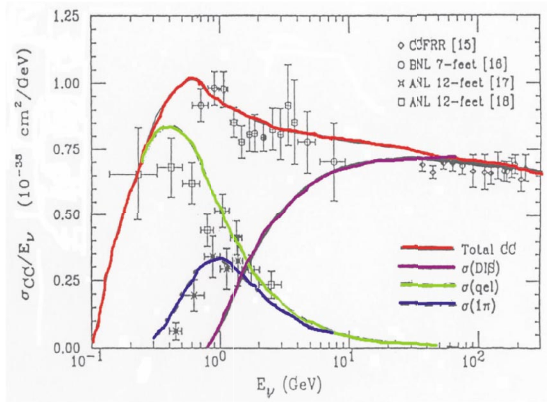

Fig 3. Experimental results for charged current ν_μ cross section with theoretical calculation [15]. Around 1 GeV, measurement precision is about 30% level.

scattering ($\nu_\mu + n \rightarrow \mu + p$) and charged current single pion (CC1π) production ($\nu_\mu + N \rightarrow \mu + N + \pi$), where N is a nucleon. The axial vector mass in the dipole formula of the nucleon form factor is set to be 1.1 GeV/c^2 for both QE and CC1π interactions [8]. CC coherent pion production is simulated based on the Rein and Sehgal model [9]. For deep inelastic scattering (DIS), we use GRV94 nucleon structure functions [10] with a cross section correction by Bodek and Yang [11], which reduces the cross section on average by 25% for the K2K neutrino energy spectrum. As for the final state hadrons, we simulate it with a custom-made program [12] and PYTHIA/JetSet pacakge for the hadronic invariant mass, W, $1.3 - 2.0$ GeV/c^2 and larger than 2.0 GeV/c^2, respectively. Nuclear effects are taken into account in the ν-C scattering. As for the pions originating from neutrino interactions, absorption, elastic scattering and charge exchange inside the target nucleus are simulated. Pion cross sections are calculated using the model by Salcedo et al. [13] which is agreed well with the past experimental data [14].

4. Physics Output from SciBar

Figure 3 shows current cross section measurement around 1 GeV neutrino energy region [15]. The precision for each interaction mode are about 30% level around this region. Because many atmospheric and accelerator-based neutrino oscillation experiments use interactions of neutrinos in this energy region and the uncertainty will become severe limitation of the precision in the future, we need precise measurements of neutrino-nucleus interaction. We will improve the measurement with SciBar, which has good tracking and PID performance as mentioned above. The following topics are measurable with SciBar.

- E_ν spectrum at near site from CCQE
- Form factors for CCQE and CC1π ($\nu_\mu + N \rightarrow \mu + N + \pi$)
- Cross section for CC1π as a function of E_ν
- Cross section for CC coherent pion production ($\nu_\mu + A \rightarrow \mu + A + \pi$)
- Cross section for CC multi pion production
- Cross section for neutral current (NC) elastic and single pion production
- NC/CC cross section ratio
- ν_e contamination in the beam

In the following, we present the charged current analysis with SciBar.

5. Charged current analysis

5.1. Event selection

Charged current (CC) events are selected by requiring that at least one reconstructed track starting in the fiducial volume of SciBar is matched with a track or hits in the muon range detector (MRD) [16] located just behind SciBar (SciBar-MRD event). With this criterion, the threshold for muon momentum, p_μ, is 450 MeV/c. According to the Monte Carlo (MC) simulation, 98% of the events selected by the requirement are CC induced events, and the rest are neutral current (NC) interactions accompanied by a charged pion or proton track which penetrates into the MRD. The momentum of the muon is reconstructed from its range through SciBar and MRD. The resolutions for p_μ and angle with respect to the neutrino beam direction θ_μ are determined with 80MeV/c and 1.6 degrees.

Event with one or two reconstructed tracks are used for this analysis. The sample of two track events is divided into two categories by using kinematic information. The expected direction of the recoil proton is calculated using p_μ and θ_μ assuming QE interaction. The events in which the angular difference between the expected and observed direction of the second track is less than 25 degrees are classified as the QE sample and others are classified into the nonQE sample. With this criterion, QE interaction is identified with an efficiency of 79% out of all two track QE events and with a purity of 72%. Figure 4 shows distributions of the muon momentum (p_μ), angle with respect to the beam direction (θ_μ), and reconstructed square of four momentum transfer for each sub-sample, where expectation from the MC simulation, normalized by the total number of SciBar-MRD events, is overlaid.

The value of q^2 reconstructed from p_μ and θ_μ under the assumption of QE interaction is calculated using

$$p_\nu = \frac{1}{2}\frac{(M_p^2 - m_\mu^2) + 2E_\mu(M_n - V) - (M_n - V)^2}{-E_\mu + (M_n - V) + p_\mu \cos\theta_\mu}$$

where $M_{p(n)}$ is the proton (neutron) mass, m_μ is the muon mass and V is the nuclear potential set at 27 MeV. The resolution of q^2_{rec} for QE events with q^2 less than 0.10 $(\mathrm{GeV/c})^2$ is determined to be 0.01 $(\mathrm{GeV/c})^2$.

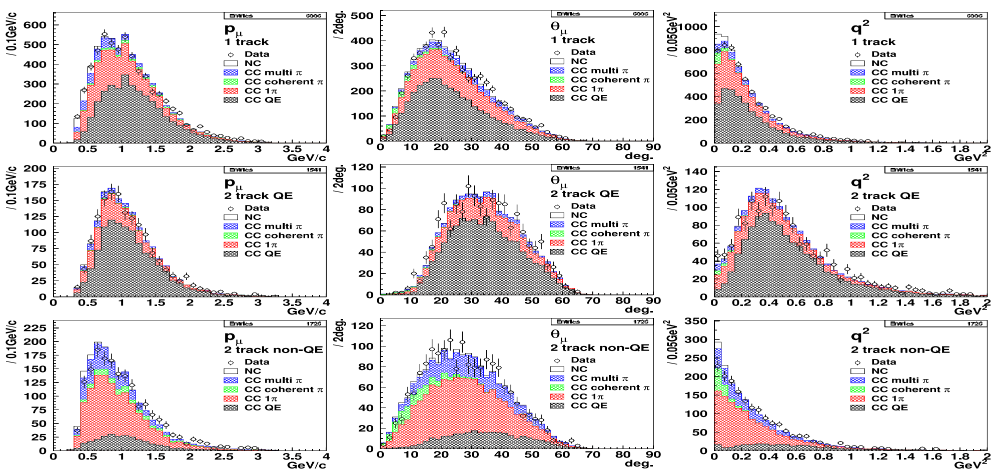

Fig 4. The muon momentum, angular and reconstructed q^2 distributions for SciBar sub-samples. The Monte Carlo distributions, normalized by the total number of events, are overlaid. (Each interaction mode is located in order of CCQE, CC1π, CC coherent π, CC multi π and NC from the bottom.)

The agreement between the data and MC simulation is good for all samples. However, we observed a small but significant discrepancy for the low-q^2 (small angle scattering) region in 1Track and 2Track non-QE enriched samples. This discrepancy is also observed by other near detectors and the MiniBOONE experiment [17], which means it is not due to the detector systematics. Furthermore, this discrepancy cannot be explained by uncertainty of the neutrino energy spectrum. Therefore, the neutrino interaction model is considered to be the source of the observed disagreement. As shown in Figure 4, dominant process in low q^2 region of 1Track and 2Track non-QE enriched samples are resonance π production ($\nu_\mu + N \rightarrow \mu + N + \pi$) and coherent π production ($\nu_\mu + A \rightarrow \mu^- + \pi^+ + A$). We note that the MiniBOONE sample is dominated by the quasi-elastic events.

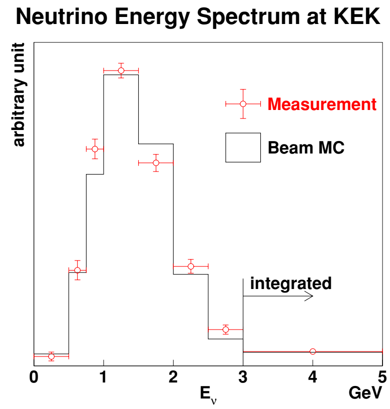

Fig 5. The E_ν spectrum measurement with near detector complex compared with Beam MC simulation.

5.2. E_ν spectrum shape

The neutrino energy spectrum is determined by performing the χ^2 fitting on the two-dimensional distribution of p_μ versus θ_μ with the MC expectations. The fitting parameters are E_ν divided into eight energy region and the CC-nonQE to QE overall cross section (R_{nqe}) which is relative to the prediction from our using model [2]. The systematic uncertainties are also incorporated as the fitting parameters which are the energy scale, track finding efficiency and nuclear effects. As mentioned above, we have significant discrepancy for forward going muon events. Therefore, to avoid a bias from this uncertainty, we perform the E_ν fit using only data with $\theta_\mu > 10$ degrees. The χ^2 value of the best fit is 538.5 for 479 degree of freedom (DOF) including the other near detectors data. The measured neutrino spectrum is shown and listed in Figure 5 and Table 1. For R_{nqe}, the best fit value is 0.95.

Table 1. The E_ν spectrum fit results. $\Phi_{\rm ND}$ is the best fit value of flux for each E_ν bin. It is given relative to the 1.0–1.5 GeV bin. The percentages of uncertainties in $\Phi_{\rm ND}$ is also shown.

E_ν (GeV)	$\Phi_{\rm ND}$	$\Delta(\Phi_{\rm ND})$
0.0 – 0.5	0.032	46
0.5 – 0.75	0.32	8.5
0.75 – 1.0	0.73	5.8
1.0 – 1.5	≡ 1	—
1.5 – 2.0	0.69	4.9
2.0 – 2.5	0.34	6.0
2.5 – 3.0	0.12	13
3.0 –	0.049	17

5.3. Low-q^2 correction and R_{nqe}

After evaluating the spectrum shape with the restricted θ_μ regions, we apply the following correction based on the study with SciBar non-QE sample for the low-q^2 events. From the discussion in Section 5.1, the possible sources of this deficit are CC resonance π production or CC coherent π production. For CC resonance π production, a phenomenological suppression of q^2/Λ for $q^2 < \Lambda$, where $\Lambda \sim 0.10$ reproduces data, while non-existence of coherent pion also reproduce data. Currently, we do not judge which is the main cause of the deficit. To check the agreement of these tuned MC with real data, we re-fitted the (p_μ, θ_μ) distribution with the fixed spectrum and data for all θ_μ region, where only R_{nqe} is the fitting parameter. The best fit value is 1.02 (1.06) for R_{nqe} with χ^2/DOF of 638.1/609 (667.1/606) when CC resonance (coherent) π production is corrected. Although the choice of these tuning method does not affect the oscillation analysis result at all, R_{nqe} is changed as shown above. So we additionally assigned the error of 0.1 on R_{nqe} to cover the value for all fitting condition, while the statistical error size is only 3% level.

6. SciBar low-q^2 study

As discussed in the precious section, we found a significant discrepancy between data and the MC prediction in low-q^2 region. We confirmed the non-QE interaction, mainly CC1π and CC coherent π, is the source of the deficit for our case. Since this uncertainty affects the cross section measurement much more than the statistical uncertainty, to identify the cause of this problem is important.

Figure 7 shows schematic views of CC resonance π production and CC coherent π production. In the SciBar, when the pion is absorbed inside a target nucleus or proton momentum was below tracking threshold, CC1π is detected as a two track event of $\mu - p$ or $\mu - \pi$, while CC coherent π is completely detected as $\mu - \pi$ event. Therefore, by applying particle identification on the second track of nonQE sample, CC1π and CC coherent pion are effectively separated.

Figure 7 shows q^2_{rec} distribution for nonQE sample with proton-like second track (nonQE-proton sample) and with pion-like second track (nonQE-pion sample). As shown in the figure, clear deficit is seen only in the nonQE-pion sample. CC coherent pion production dominates events in this region. Therefore, it is most suspicious mode as a cause of low-q^2 deficit. For CC coherent π production, many past experimental data exist in the neutrino energy region from 7 to 100 GeV, while there is no measurement at lower energies. As shown above, SciBar is expected to detect this mode with high purity and efficiency thanks to its excellent PID performance. Furthermore, because SciBar is a fully active

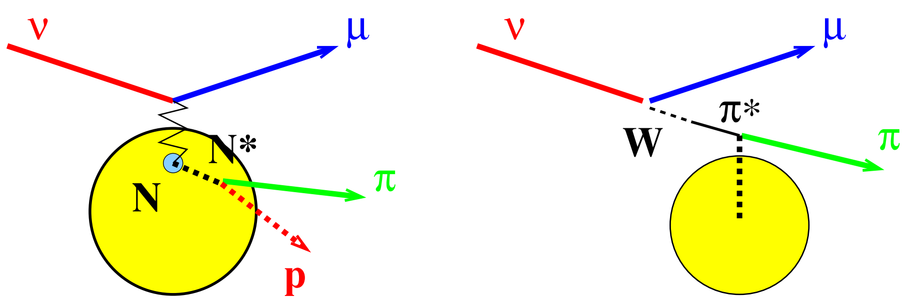

Fig 6. Schematic views of CC resonance π production (left) and CC coherent π production (right). For CC resonance π, when pion is absorbed inside the target nucleus or proton momentum is below detection threshold, the event is detected as 2 track sample.

detector and detects a short range proton as a vertex activity, purity is expected to be improved up to more than 50%. Cross section measurement for coherent π production is now on-going and the result, which is the first experimental result with a few GeV neutrinos, will be released soon.

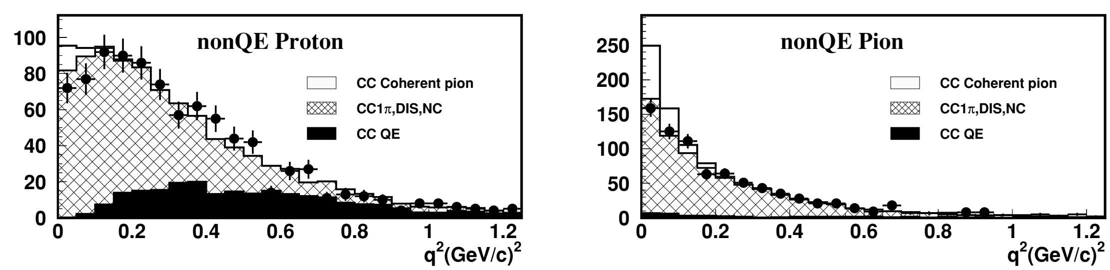

Fig 7. The reconstructed q^2 distributions for nonQE sample with proton-like second track (left) and nonQE sample with pion-like second track (right). For nonQE-pion sample, clear deficit is seen in the low-q^2 region, where CC coherent pion production dominates events in this region.

7. Other on-going work with SciBar

In this section, we briefly introduce other on-going analysis with SciBar.

7.1. CCQE M_A measurement

The differential cross section for CCQE interaction is studied in terms of the axial vector mass, M_A. This is the first measurement of M_A for a carbon target.

7.2. CC1π cross section measurement

This process is a dominant background for neutrino energy spectrum measurement at SK site and expected to be a main systematic source for future precise oscillation study with high intensity proton accelerator such as T2K. It is expected to be measurable with about 5% accuracy for this cross section including final state processes, statistically.

7.3. ν_e flux measurement

For the ν_e appearance search, which is also the main purpose of K2K experiment together with ν_μ disappearance measurement, the evaluation of ν_e contamination in the neutrino beam before oscillation is important. The ν_e/ν_μ flux ratio is studied and expected to be measured with the precision of less than 10% statistically.

7.4. NC π^0 cross section measurement

Currently, dominant background for ν_e detection with water cherencov detector is this process and its cross section uncertainty becomes one of the largest systematic uncertainty for ν_e appearance search. NC π^0 cross section is expected to be measured with about 10% precision statistically, which is almost comparable with K2K-1kt measurement [19].

8. conclusion

SciBar was constructed to improve the determination of neutrino energy spectrum and to study the neutrino interaction around a 1 GeV neutrino energy region in detail. In this article, distributions of p_μ, θ_μ and q^2 for charged current interaction are compared with the MC expectation. Agreement between data and the MC expectation is found to be good except for the forward going muon events. We have confirmed the source of this discrepancy for K2K case is nonQE interaction, especially coherent π production, is most suspicious mode from SciBar data. Further study on coherent π production is going and the precise result for its cross section around 1 GeV region is expected to be released in near future, as well as detailed knowledge of other neutrino-nucleus interaction properties.

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