Studies on C.C. Quasi-Elastic and Inelastic Events by the K2K Fine-Grained Detector

T. Ishida[a], on behalf of the K2K collaboration

[a]Institute of Particle and Nuclear Studies, High Energy Accerelator Research Organization (KEK), 1-1 Oho, Tsukuba-shi, Ibaraki 305-0801, Japan

The Fine-Grained Detector is one of the two near-site neutrino detectors employed in the K2K long-baseline neutrino-oscillation experiment. It has played an essential role to determine the neutrino flux at production and to measure the ratio of the charged-current inelastic cross section to the quasi-elastic cross section, both of which are very necessary inputs to test the oscillation hypothesis at the far site, Super-Kamiokande. In this talk I describe observations of this detector in detail. Recent progress on low-energy event analysis, and on q^2 analysis, to obtain the axial vector mass M_A, are also reported.

1. Introduction

K2K is the first long-baseline neutrino oscillation experiment in operation[1]. A wide-band neutrino beam with an average energy of 1.3 GeV is produced by the KEK 12 GeV PS towards Super-Kamiokande (SK), located 250 km west from KEK. We also employ a near detector system located 300 m downstream from the primary target. It consists of two independent detectors: a 1 kiloton SK-like water Cherenkov detector ($1kt$) and a tracking detector with fine granuarity (Fine-Grained Detector, FGD). From 1999 to 2001, 5.6×10^{19} protons on target were delivered to the K2K experiment in 235 days of running. In this period the near detectors have also accumulated data of neutrino-nucleus interactions with significant statistics.

Recently, we have obtained an indication of the $\nu_\mu \rightarrow \nu_X$ neutrino oscillation by testing the deficit of ν_μ events and a distortion of the neutrino spectrum observed at SK[4]. The neutrino spectrum at production, which is a very necessary input for the oscillation test, is obtained by employing a χ^2 fit on the muon momentum and angular distributions observed by the near detectors. The ratio of the charged current inelastic cross section to the quasi-elastic cross section is also an important input to be measured by the near detectors, because a large portion of SK events are from charged-current inelastic interactions. The overall procedure of the spectrum reconstruction is as presented in this workshop[5]. In this talk I will describe the FGD data and its analysis procedure in more detail. The FGD events are responsible for measuring the neutrino flux in E_ν >1 GeV region and are also to determine the nonQE-to-QE ratio, R_{nqe}, by its tracking capability. Also, recent progress on FGD analyses, study of events with an energy less than 1 GeV, and the CCQE M_A analysis result, are also introduced briefly.

2. Studies on C.C. inelastic/quasi-elastic events

2.1. Event selection and $\Delta\theta_P$ distribution

FGD consists of a scintillating fiber tracker (SciFi)[2], plastic scintillator veto/trigger counters surrounding the SciFi, an electromagnetic calorimeter of 600 lead-glass blocks (LG)[1], and a muon range detector (MRD)[3]. The SciFi tracker has a $2.6m\times2.6m\times1.7m$ rectangular shape. It is composed of 19 layers of $6cm$-thick water containers, sandwiched with $20\times(yy\text{-}xx)$ layers of scintillating fibers. The track-finding efficiency of SciFi is 70% for a track passing through three layers of scintillating fiber and close

[1]It was removed in September '01. A new detector, SciBar, will be installed in the space during the summer shutdown of '03.

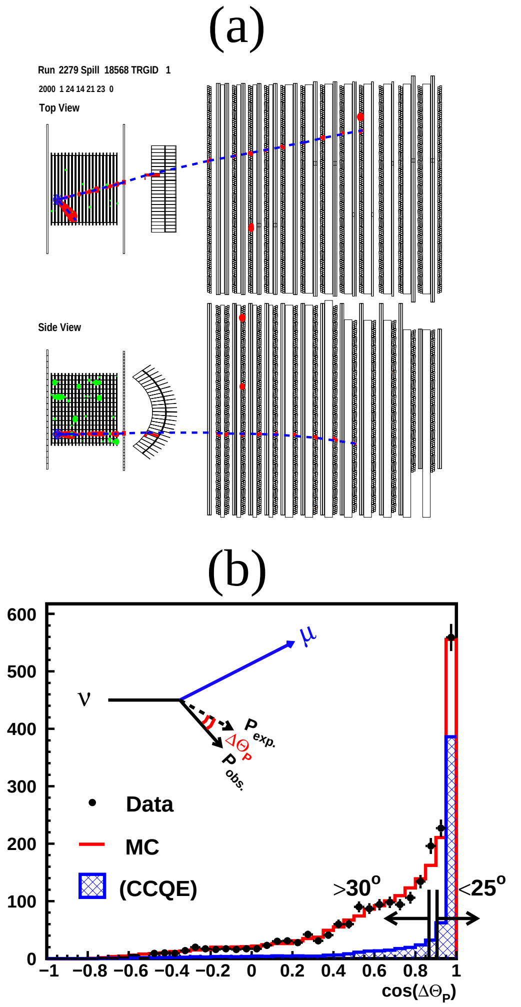

Figure 1. *(a) Typical FGD two-track events with a vertex in the SciFi. It is a candidate of a CCQE interaction,* $\nu_\mu + n \rightarrow \mu + P$. *Track-associated hits are represented by red circles with their size proportional to the number of pixels in the hits. (b)* $cos(\Delta\theta_P)$ *distribution for two-track samples. It is used to distinguish CCQE / non-QE enhanced samples.*

to 100% for more than 5 layers[7]. For neutrino spectrum reconstruction, we choose SciFi-MRD events based on the following criteria:

- A vertex with track(s) with a length $\geq$ 3 SciFi layers is reconstructed. The fiducial volume is defined as a rectangle with Δx and $\Delta y \leq 1.1m$, covering the 1^{st} to 17^{th} water containers (fiducial mass= 5.9 t).
- A SciFi track should match to a hit of the downstream veto/trigger counters, so that the interaction is in a beam spill.
- The track also should match to a LG cluster, and to a MRD track and/or hit cells. It guarantees that the track passes the LG cells, and is thus a minimum-ionizing muon.

With all of these cuts, the *net* efficiency in the fiducial volume is estimated to be ~45% for the CCQE interactions and ~31% for the CC-*inclusive* interactions.

Fig. 1(a) shows a typical FGD event with a secondary track, most probably a scattered proton. For two-track events, a kinematic variable, $\Delta\theta_P$, is defined to enhance the fraction of CCQE and non-QE interactions. Assuming a QE interaction, the direction of the scattered proton can be calculated from the muon momentum. We define $\Delta\theta_P$ as the difference between the observed direction of the second track and that of the expectation. Fig. 1(b) shows the $cos(\Delta\theta_P)$ distribution. CCQE events, shown by a hatched histogram, concentrate around $cos(\Delta\theta_P) = 1$, *i.e.* $\Delta\theta_P = 0$. We select a CCQE enhanced sample by requiring a $\Delta\theta_P$ within 25 degrees, and non-QE enhanced samples by a $\Delta\theta_P$ of more than 30 degrees, respectively. In the CCQE enhanced sample, 62% of the events are to be QE events. In the non-QE enhanced sample, 82% of events come from interactions other than CCQE. The FGD events are divided into three event categories: (1) 1-track, (2) 2-track CCQE enhanced, and (3) 2-track non-QE enhanced samples, respectively. Here, it is to be noted that the non-QE to QE ratio, R_{nqe}, is strongly constrained by the ratio of the event numbers, (3)/(2). The observed number of events for each event category are summarized in Table 1.

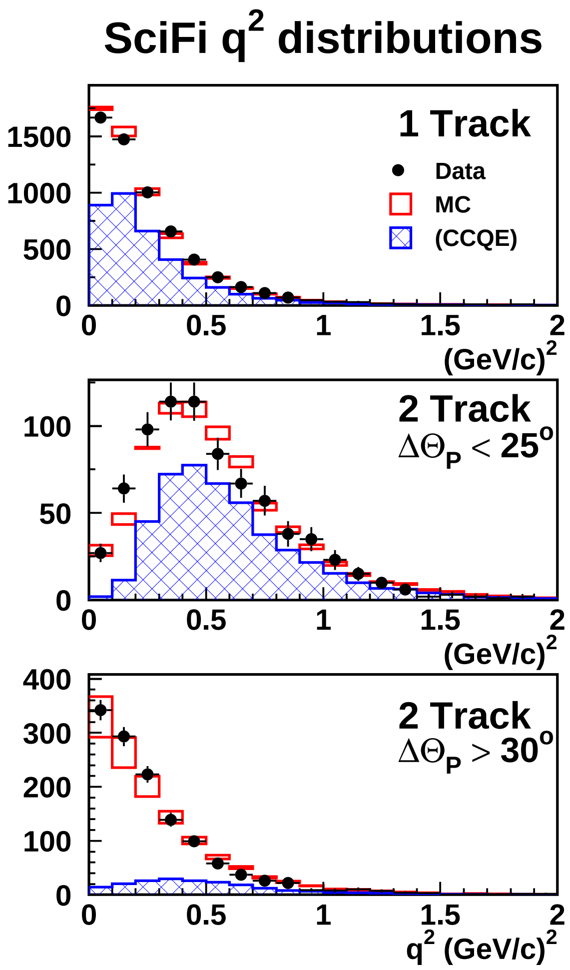

Figure 2. *q^2 distributions for each category of the SciFi events, calculated from the muon momentum by assuming CCQE kinematics. The crosses are data and the boxes are the tuned MC with the best-fit parameters. The errors in the MC distributions correspond to the uncertainties of each flux bin and R_{nQE}. The hatched histograms show the CCQE contributions.*

Table 1
Statistics of the Fine-Grained Detector events for each category used in the spectrum analysis, which coresponds to 3.970× 10^{19} p.o.t. in total.

		# Events	*dof.*†
SciFi-MRD		8,393	
Single Track	**(1)**	5,963	44
2-track $\Delta\theta_P \leq 25°$	**(2)**	764	40
2-track $\Delta\theta_P > 30°$	**(3)**	1,288	40

† Number of points on the (p_μ, θ_μ) plane used in the spectrum reconstruction fit.

2.2. Proton re-scattering

Meanwhile, for the number of track distribution and for the $cos(\Delta\theta_P)$ distribution, we have realized that the final state interaction of a scattered proton plays an essential role. About 40% of the protons with their momentum greater than 400 MeV/c re-scatter with nucleons inside of oxygen nuclei, and lose about 90 MeV/c of the momentum. As a result, the events appear as single-track events or two-track events with a large $\Delta\theta_P$. To obtain better agreements to the data we have newly introduced the proton rescattering effect into our Monte Carlo simulation, which was not taken into account so far[8]. To validate the simulation it was compared to the existing *ep* backward scattering data, $e +^{12} C \rightarrow e' + p + X$[9]. We have found that the ratio between backward-scattering and forward-scattering agrees within a 10% error. In a spectrum reconstruction fit, we introduced this term as one of the systematic errors.

2.3. Spectrum reconstruction fit

To reconstruct the neutrino spectrum at production, the 2-dimensional distributions of the muon momentum versus the angle with respect to the beam direction are fitted with respect to MC distribution. As physical fitting parameters, we use a re-weighting factor of the incoming neutrino flux, devided into 8 bins, and the nonQE-to-QE ratio, R_{nqe}, taken to be unique for the entire energy region. The systematic uncertainties, *i.e.* the energy scales, the track finding efficiencies, and the detector thresholds, are incorporated as other fitting parameters.

As a result, it was found that the best-fit results of the flux re-weighting factors stay mostly around unity within a 10% error. Also, the detector systematics were found to lie within their expected errors. The fitted value of R_{nqe} is 0.93, where an error of 20% is assigned based on the disagreement of SciFi and $1kt$ independent fitting results. A SciFi-only fit can determine the R_{nqe} value within a 10% error. In Fig. 2, the q^2 distributions of each event category, calculated from the muon momentum by assuming CCQE kinematics, are overlaid with the flux re-weighted MC. The errors on the MC distributions correspond to the 1-sigma uncertainties of each flux bin and R_{nQE}, with their correlations taken into account. As can be seen, the data-to-MC agreement looks reasonably good for each event category. Honestly speaking, this owes much to the MC tuning, which takes place prior to the spectrum reconstruction.

2.4. MC model tuning

In the previous workshop, various data-to-MC overlays of charged current inclusive interactions were shown[6]. Although the overall agreements for the muon momentum and angular distributions appeared to be quite fine, we observed a small, but significant, discrepancy for the low-q^2 (small scattering angle) region, which is a common tendency between $1kt$ and FGD. Due to the disagreement, the spectrum analysis couldn't give a satisfactory χ^2. This indicates that the disagreements can not be due to the neutrino flux uncertainties nor to the detector systematics, but to the neutrino interaction models, themselves.

Our MC treats neutrino-nucleus interactions through four branches[10]: CC Quasi elastic scattering (CCQE), CC 1π production through baryon resonances (CC1π), coherent π production, and deep inelastic scattering. To tune the neutrino interaction Monte Carlo simulation, we have introduced a phenomenological weight as a function of q^2 to reproduce the following models, respectively:

- In CCQE scattering, the axial vector mass M_A in the dipole formula is set to a central value of 1.1 GeV/c^2.
- The axial mass for CC1π is set to a central value of 1.2 GeV/c^2[11].
- For coherent pion production, a model by Marteau[12] is used.
- For deep inelastic scattering, the structure function by Bodek and Yang[13] is employed.

It should be noted that we do not intend to validate these models. These corrections simply tend to make the q^2 distribution harder compared to our old version of MC, and thus make the data-to-MC agreements of q^2 distributions better.

As for the ^{16}O target, nuclear effects, such as the Fermi motion of the nucleon, the nuclear potential, and the Pauli blocking effect for the final state nucleon, are known to be very important. MC tuning for these effects are also taking place with respect to the existing ep scattering data[14].

3. On-going analyses

3.1. Low-energy events

So far in FGD event analysis, we require a SciFi track to be matched to a MRD track or a hit. Although the requirement guarantees that the track is a muon, it also limits the p_μ sensitivity to a range greater than ~500 MeV/c. This is the reason why the spectrum fit in the low-energy region is mainly due to the $1kt$ data. Because flux distortion due to the oscillation is expected in the energy region around $0.5 \sim 0.75$ GeV, it is also very important for FGD to achieve more sensitivity in the lower energy region and to check the consistency between the $1kt$ result. For that purpose, we are studying events with primary tracks that stop in the lead-glass module (SciFi-LG events). Fig.3 shows the p_μ and θ_μ distributions for SciFi-LG single-track samples, overlayed with the tuned MC without any fitting. As can be seen, all of the samples have a muon momentum less than 1 GeV/c.[2] By including these events, it is expected that we can obtain 45% more events in the E_ν <1 GeV region.

[2]The muon momentum is reconstructed by using the LG response. The procedure is validated by the pion beamtest data.

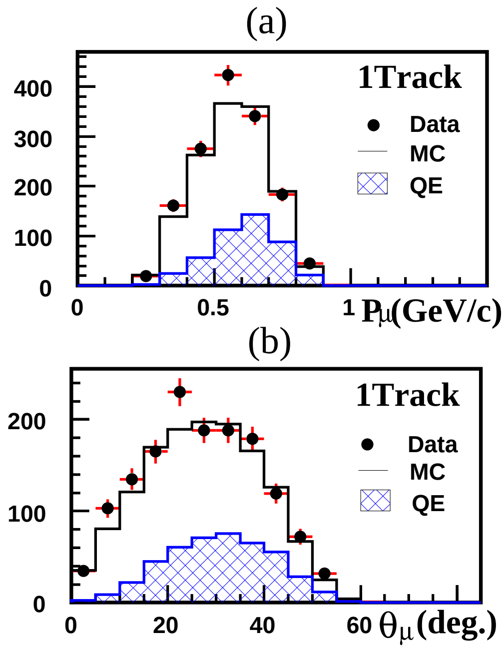

Figure 3. *(a) p_μ and (b) θ_μ distributions for SciFi-LG single track samples, overlayed with the tuned MC without a fitting. The errors in the distributions are only statistical. The hatched histograms show the CCQE contributions.*

The LG module intends to measure the ν_e component in the beam during production. After data taking until July, 2001, we decided to remove it because we have enough data for our purpose. Data taking without LG blocks will start in December, 2002, and is scheduled to continue until July, 2003, when installation of a new detector module (SciBar) will take place. It will supply us more low-energy events with sufficient statistics.

3.2. Q^2 analysis, sensitivity to C.C. Quasi-Elastic M_A

The differential cross section, $\frac{d\sigma}{dq^2}(E_\nu, q^2)$, for the CC quasi-elastic interaction, $\nu_\mu + n \rightarrow \mu + p$, has been studied in terms of the axial vector mass, M_A. This is the first measurement of M_A with a water target. Although the cross section is almost in proportion to the value of M_A, the measurement of the absolute cross section is a difficult task. Fig.4(a) shows the q^2 dependence of the CCQE differential cross section[15] in our beam energy for three different M_A values, which are normalized by area. As can be seen, the q^2 dependence of the cross section does not change very much in terms of M_A. In a flux-independent (shape-only) fit we are requested to distinguish these slight differences.

In Fig.(b), MC histograms are shown for SciFi 2 track QE-enhanced and nonQE-enhanced samples (the same plots as in Fig.2), where the plots are devided into each interaction mode. By using FGD samples in three event categories, we are trying to fit the entire q^2 region in different E_ν bins simultaneously in terms of M_A. A preliminary analysis has shown us the error of the M_A value to be about 0.2 GeV/c^2, where the statistical error is only 0.06 GeV/c^2. Meanwhile, systematic errors, which are 0.15 GeV/c^2 in total, mainly come from the uncertainty in the CC single-pion cross section,[3] and also the uncertainty in the nuclear effect. It should be noted that in the low-q^2 region nuclear effects play essential roles. For example it is known that the free-neutron cross section should be corrected by the factor of ~45% in the q^2<0.2 (GeV/c)^2 region, which accounts for the Pauli exclusion principle. To solve these uncertainties, we definitely need more efforts, to refer results of other experiments and to try other theoretical models.

4. Summary

On the way to the K2K oscillation analysis, FGD data provide a neutrino flux at production in the $E_\nu > 1$ GeV region and a charged-current nonQE-to-QE ratio, R_{nqe}, of 0.93 ± 0.2 with respect to our tuned Monte-Carlo value, 1.0. It is shown that R_{nqe} can be determined within an accuracy of 10% by a FGD-only fit, which is strongly constrained by the 2-track non-QE enhanced and QE enhanced samples.

We are making efforts to reduce the energy threshold by using LG-stopping samples. We have obtained 45% more events in the E_ν<1 GeV

[3] Our fit also has sensitivity for CC1π M_A value, because our nonQE-enhanced sample is dominated by CC1π mode.

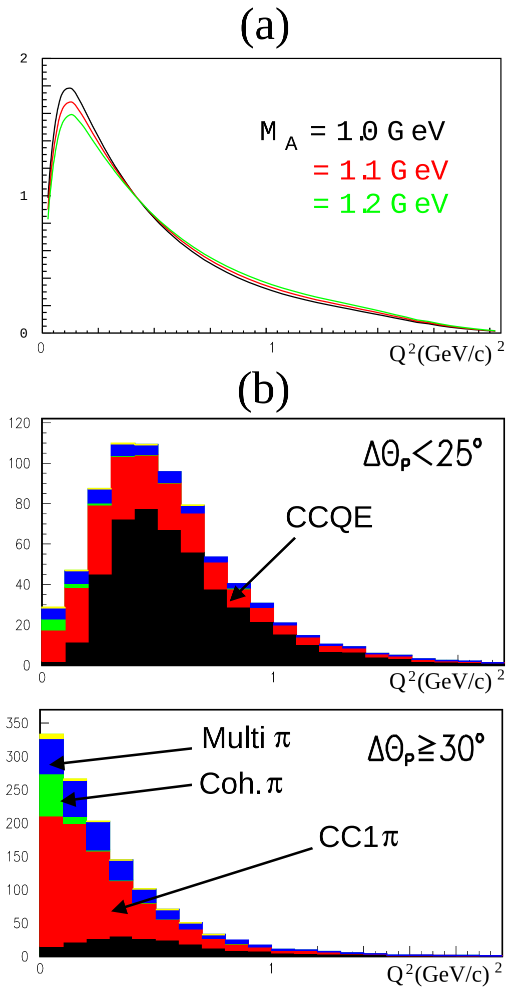

Figure 4. *(a) q^2 dependence of the CCQE differential cross section (E_ν=1.3 GeV) for three different axial vector mass values: 1.0, 1.1 and 1.2 GeV/c^2. The plots are normalized by area. (b) MC prediction of q^2 distributions for SciFi 2-track QE-enhanced / nonQE-enhanced samples, divided into each interaction mode (the same MC distributions as are in Fig.2).*

region. Data-to-MC agreements are reasonable enough for these event samples. Runs without LG will be started this December, and we will obtain more low-energy events in the E_ν<0.5 GeV region also, until a brand new detector, SciBar, is installed in the summer of 2003.

A q^2 analysis will determine the CC quasi-elastic M_A. It is the first measurement of M_A with a water target. The preliminary analysis gives the accuracy of M_A to be 0.2 GeV/c^2, where the statistical error is only 0.06 GeV/c^2. Efforts to reduce the systematic uncertainties are needed, in cooperation with colleagues in the NuInt workshop attendees.

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