Search for coherent charged pion production in neutrino-carbon interactions

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(Dated: April 22, 2005)

We report the result from a search for charged-current coherent pion production induced by muon neutrinos with a mean energy of 1.3 GeV. The data are collected with a fully active scintillator detector in the K2K long-baseline neutrino oscillation experiment. No evidence is observed and an upper limit of 0.60×10^{-2} is set on the cross section ratio of coherent pion production to the total charged-current interaction at the 90% confidence level. This is the first experimental limit for the coherent charged pion production in the energy region of a few GeV.

PACS numbers: 13.15.+g,25.30.Pt,95.55.Vj

This Letter presents the result from a search for charged current (CC) coherent pion production by neutrinos with energies of a few GeV using the accelerator-produced ν_μ beam in the KEK to Kamioka long-baseline neutrino oscillation experiment (K2K). The CC coherent pion production in neutrino-nucleus scattering, $\nu_\mu + A \rightarrow \mu^- + \pi^+ + A$, is a process in which the neutrino scatters coherently off the entire nucleus with a small energy transfer. It has been measured in a number of experiments [1–5], providing a test of the partially conserved axial-vector current (PCAC) hypothesis [6]. The existing data agree with the Rein and Sehgal model [7] based on the PCAC hypothesis in the neutrino energy region from 7 to 100 GeV, while there is no measurement available around 1 GeV. The recent discovery of neutrino oscillations has renewed interest in the neutrino-nucleus interaction in the sub to few GeV region. Many atmospheric and accelerator-based neutrino oscillation experiments use interactions of neutrinos in this energy region. Therefore, precise knowledge of them is indispensable to improve the accuracy of the neutrino oscillation measurements. In this Letter, we compare our result with the Rein and Sehgal model [7] because it is the only model that provides the kinematics of pions and is commonly used in neutrino oscillation experiments.

In the K2K experiment, protons are extracted in a 1.1μs spill every 2.2 seconds from the KEK 12 GeV proton synchrotron and hit an aluminum target. Positively charged secondary particles, mainly pions, are focused by a magnetic horn system and decay to produce an almost pure (98%) ν_μ beam with a mean energy of 1.3 GeV [8, 9]. The neutrino beam energy spectrum and profile are measured through neutrino interactions by the near neutrino detectors located 300m downstream from the target. An estimation of the absolute flux has large ambiguity due to uncertainties in the primary proton beam intensity, the proton targeting efficiency, and hadron production cross section. Therefore, instead of deriving the absolute cross section for CC coherent pion production, the cross section ratio to the total CC interaction is measured. The data are collected with one of the near detectors, fully active scintillator detector (SciBar), from October 2003 to February 2004, corresponding to 1.7×10^{19} protons on target (POT).

The SciBar detector [10] consists of 14,848 extruded plastic scintillator strips read out by wavelength shifting fibers and multi-anode PMTs. 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. Scintillator strips with dimensions of $1.3 \times 2.5 \times 300$ cm^3 are arranged in 64 layers. 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 this analysis. Due to the fine segmentation, the minimum reconstructable track length is 8cm. A track finding efficiency of more than 99% is achieved for a single track with a track length of more than 10cm. The track finding efficiency for a second, shorter track is lower than that for the single track due to overlap with the primary track. This efficiency increases with track length and reaches 90% at a track length of 30cm. In SciBar, the experimental signature of CC coherent pion production is the existence of exactly two tracks, both consistent with minimum ionizing particles, and low momentum transfer defined as $q^2 \equiv (P_\mu - P_\nu)^2$, where P_μ and P_ν are four momentum of muon and neutrino, respectively.

The NEUT program library [11] is used to simulate the neutrino interactions with the nucleus. CC coherent pion production is simulated based on the Rein and Sehgal model [7]. The cross section averaged over the K2K neutrino energy spectrum is 2.85×10^{-40}cm^2/nucleon for carbon. The Lewellyn Smith model [12] and the Rein and Sehgal model [13] are employed for quasi-elastic (QE) 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, respectively. 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 [14]. For deep inelastic scattering (DIS), we use GRV94 nucleon structure functions [15] with a correction by Bodek and Yang [16], which reduces the cross section by 25% on average for the K2K neutrino energy spectrum. Nuclear effects are taken into account in ν-C scattering. As for the pions originating from neutrino interactions, absorption, elastic scattering and charge exchange inside the target nucleus are considered. Pion cross sections are calculated using the model by Salcedo et al. [17] which agrees with past experimental data [18], while pion interaction outside the targed nucleus is simulated based on the other expetimantal data [19].

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) [20] located just behind SciBar (SciBar-MRD sample). 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 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 the angle with respect to the neutrino beam direction θ_μ are 80MeV/c and 1.6 degrees. The CC events with one or two reconstructed tracks are selected. The sample of two track events is divided into two categories of QE sample and non-QE sample by using kinematic information [21]. The second track in the non-QE sample is then classified as proton-like (non-QE-proton) or pion-like (non-QE-pion) 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 proton efficiency of 90%.

The CC coherent pion candidates are extracted from the non-QE-pion sample. The major background is CC1π interaction with proton, $\nu_\mu + p \to \mu^- + \pi^+ + p$, where the proton is below threshold or overlapping with other particle tracks. Some of those events are rejected by requiring the pion-like track goes forward due to the momentum conservation for beam direction. Even if the proton is not reconstructed as a track, it can be detected as a large energy deposit in the vertex strip or additional hits around the vertex. Figure 1(a) shows a distribution of energy deposit in the vertex strip for the non-QE pion sample. The MC prediction for the distribution of energy deposit in the vertex strip is verified with the QE sample, which has no contribution from non-visible particles, as shown in Fig. 1(b). The events with the energy deposit less than 7 MeV and no additional hits around the vertex strip are selected. Furthermore, events are required to have reconstructed q^2 less than 0.10 $(\mathrm{GeV/c})^2$; this retains about 90% of coherent pion events. We reconstruct q^2 from p_μ and θ_μ, where the neutrino momentum (p_ν) is calculated assuming QE interaction as

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

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. Although QE interaction is assumed, the q^2 for the CC coherent pion production, which is expected to be very small due to the small scattering angle for muon, is reconstructed with a resolution of 0.014 $(\mathrm{GeV/c})^2$ and shift

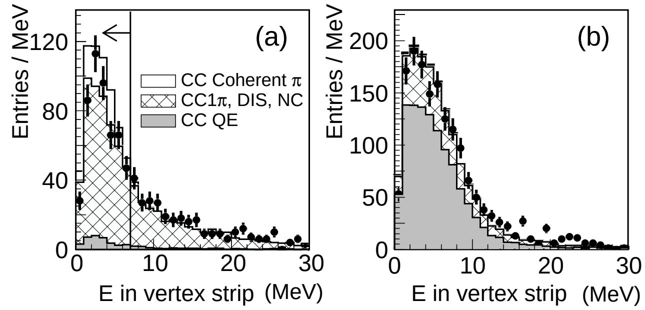

FIG. 1: Energy deposit distribution in the vertex strip for the (a) non-QE pion sample (b) QE sample. Events with activity less than 7MeV are selected.

of 0.008 $(\mathrm{GeV/c})^2$.

The background contamination in the sample is estimated by the MC simulation. In order to constrain the uncertainty due to the neutrino interaction cross section, nuclear effects, and the detector systematics, the reconstructed q^2 (q^2_{rec}) distributions of the events with q^2_{rec} more than 0.10 $(\mathrm{GeV/c})^2$ in the one track, QE, non-QE proton and non-QE pion samples are fitted simultaneously. In the fitting, the non-QE to QE relative cross section ratio, the magnitude of the nuclear effects and the momentum scale for muons are treated as fitting parameters. Figure 2 shows the q^2_{rec} distributions of the data with the MC simulation after the fitting. The χ^2 value at the best fit in the regions with q^2_{rec} greater than 0.10 $(\mathrm{GeV/c})^2$ is 73.2 for 82 degrees of freedom (DOF).

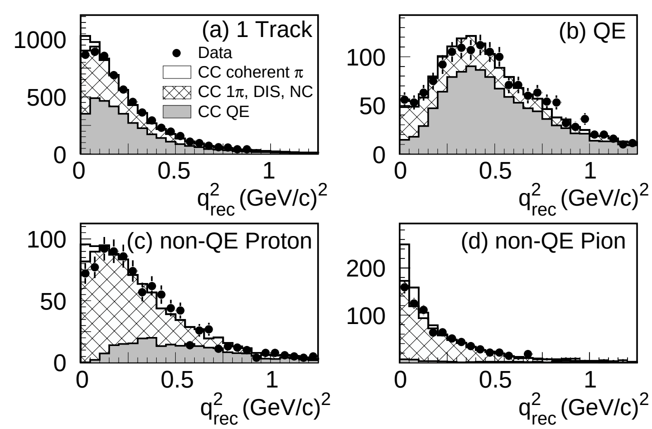

FIG. 2: The q^2_{rec} distributions for the (a) 1track, (b) QE, (c) non-QE-proton, and (d) non-QE-pion samples. Black circles show the observed data and open, hatched, and filled histograms show CC coherent pion production, CC-1π/DIS/NC, and QE events estimated by the MC simulation, respectively. All figures are normalized by the number of events with q^2_{rec} more than 0.10 $\mathrm{GeV/c}^2$.

Figure 3 shows the q^2_{rec} distribution for the final CC coherent pion sample. The number of events in each

selection step is summarized in Table I together with the efficiency and purity. In the signal region of $q^2_{\rm rec}$ less than 0.10 $({\rm GeV}/c)^2$, 113 coherent pion candidates are found. The efficiency of CC coherent pion production as a function of the neutrino energy, estimated by the MC simulation, is shown in Fig. 4. The total efficiency is 21.1%. The expected number of background events in the region is 111.4. After subtracting the background and correcting for the efficiency, the number of coherent pion events is measured to be 7.64 ± 50.40 (stat.), while 470 events are expected by the MC simulation. As a result, no evidence of coherent pion production is found in the present data set.

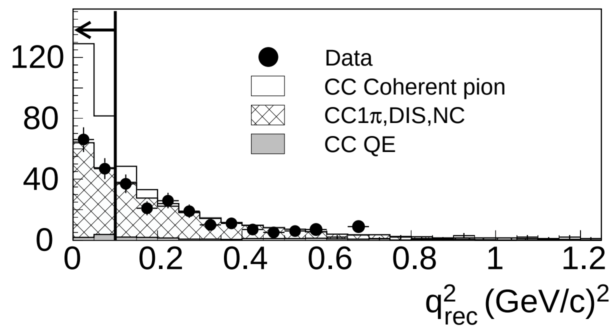

FIG. 3: The reconstructed q^2 distribution in the final sample.

	Data	Efficiency	Purity
SciBar-MRD	10049	77.9%	3.6%
Two track	3396	35.5%	5.1%
Non-QE pion	843	27.7%	14.8%
Second track direction	773	27.3%	15.8%
No activity around the vertex	297	23.9%	28.2%
$q^2_{\rm rec} \leq 0.10({\rm GeV/c})^2$	113	21.1%	47.1%

TABLE I: The number of events, the MC efficiency and purity of coherent pion events after each selection.

The total number of CC interactions is estimated by using the SciBar-MRD sample. As shown in Table I, 10049 events are identified as the SciBar-MRD sample. The detection efficiency and purity for CC interaction in the sample are estimated to be 56.9% and 98.0%, respectively, by the MC simulation. By correcting for the efficiency and purity, the total number of CC events is obtained as $(1.73 \pm 0.02({\rm stat.})) \times 10^4$. The cross section ratio of CC coherent pion production to the total CC interaction is measured to be $(0.04 \pm 0.29({\rm stat.})^{+0.32}_{-0.35}({\rm syst.})) \times 10^{-2}$.

Systematic uncertainties for the cross section ratio are summarized in Table II. The major contributions come from uncertainties of nuclear effects and the neutrino interaction model. The uncertainty due to nuclear effects

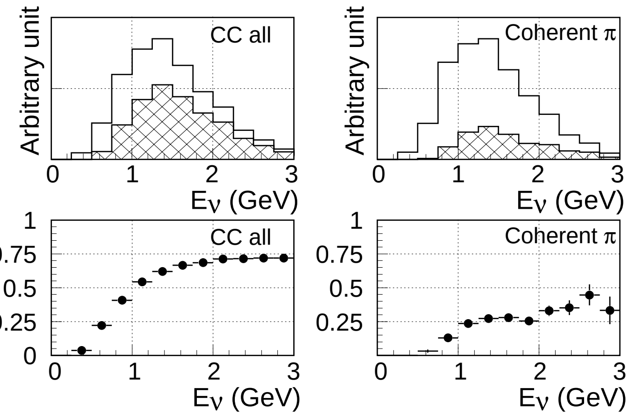

FIG. 4: Top: The neutrino energy spectrum for the total charged current events and the coherent pion events. In the figures, the hatched histgrams show the detected events. Bottom: The efficiencies as a function of neutrino energy estimated by MC simulation. Overall efficiencies are 56.9% and 21.1% for CC interaction and CC coherent pion production, respectively.

is estimated by varying the cross sections of pion absorption and elastic scattering by ±30% based on the accuracy of reference data [18]. The uncertainties in QE and CC1π interactions are estimated by changing the axial vector mass by ± 0.10 GeV/c^2. For deep inelastic scattering, the effect of the Bodek and Yang correction is evaluated by changing the correction by ±30%. The $q^2_{\rm rec}$ distribution of the non-QE proton sample indicates an additional deficit of background events in the region $q^2_{\rm rec} < 0.10$ GeV/c^2. CC1π interaction dominates events in this region, while its cross section has significant uncertainty due to nuclear effects. We estimate the amount of possible deficit with the same manner as descrived in [21] with the one track, QE and non-QE proton samples. We find that a 20% suppression of CC1π events in the $q^2_{\rm true}$ less than 0.10 GeV/c^2 is allowed, which is treated conservatively as a systematic uncertainty. The uncertainty due to pion interaction outside the target nucleus is estimated by varying the cross section based on the accuracy of the reference data [19] and found to be negligible. We also consider the uncertainties of the event selection, where the dominant error comes from track counting, detector response such as scintillator quenching, and neutrino energy spectrum shape.

Our result is consistent with the non-existence of CC coherent pion production, and hence we set an upper limit on the cross section ratio as,

$$\sigma({\rm CC~coherent}~\pi)/\sigma(\nu_\mu CC) < 0.60 \times 10^{-2}~(90\%~{\rm CL}).$$

The obtained upper limit is inconsistent with the prediction of the model by Rein and Sehgal, 2.67×10^{-2}. For reference, the total CC cross section is calculated as $1.07 \times 10^{-38}{\rm cm}^2$/nucleon in the neutrino MC simulation

Error source	uncertainty($\times 10^{-2}$)	
Nuclear effects	+0.23	-0.24
Interaction model	+0.10	-0.09
CC1π suppression	+0.14	-
Event selection	+0.11	-0.17
Detector response	+0.09	-0.16
Energy spectrum	+0.03	-0.03
Total	+0.32	-0.35

TABLE II: The summary of systematic errors in the cross section ratio

by averaging over the K2K neutrino beam energy. There are other models predicting lower cross sections [22–24], but they do not provide the kinematics of pions and it is difficult to check them directly. Assuming the relation $\sigma(\mathrm{CC}) = 2\sigma(\mathrm{NC})$ derived from isospin relation, the result is also inconsistent with the finite cross section of $\sigma(\mathrm{NC\ coherent}\ \pi) = (27 \pm 7) \times 10^{-40}\mathrm{cm}^2/\mathrm{Al}$ nucleus reported by the Aachen-Padra group [25] with an averaged beam energy of 2.0 GeV.

In summary, we report on a search for CC coherent pion production by muon neutrinos with a mean energy of 1.3 GeV. The data corresponding to 1.7×10^{19} POT are recorded with the K2K-SciBar detector. No evidence of CC coherent pion production is found and an upper limit on the cross section ratio of CC coherent pion production to the total charged current interaction is set to be $\sigma(\mathrm{coherent}\ \pi)/\sigma(\nu_\mu CC) < 0.60 \times 10^{-2}$ (90% CL). This result is the first experimental limit for charged current coherent pion production by neutrinos with energies of a few GeV.

We thank the KEK and ICRR directorates for their strong support and encouragement. K2K is made possible by the inventiveness and the diligent efforts of the KEK-PS machine group and beam channel group. We gratefully acknowledge the cooperation of the Kamioka Mining and Smelting Company. This work has been supported by the Ministry of Education, Culture, Sports, Science and Technology of the Government of Japan, the Japan Society for Promotion of Science, the U.S. Department of Energy, the Korea Research Foundation, the Korea Science and Engineering Foundation, NSERC Canada and Canada Foundation for Innovation, the Istituto Nazionale di Fisica Nucleare (Italy), the Spanish Ministry of Science and Technology, and Polish KBN grants: 1P03B08227 and 1P03B03826.

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