Search for coherent charged pion production in neutrino-carbon interactions

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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 for coherent pion production 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 90% confidence level. This is the first experimental limit for coherent charged pion production in the energy region of a few GeV.

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The charged-current (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. Such a process has been measured in a number of experiments [1–4], providing a test of the partially conserved axial-vector current (PCAC) hypothesis [5]. The existing data agree with the Rein and Sehgal model [6] based on the PCAC hypothesis in the neutrino energy region from 7 to 100 GeV, while there is no measurement available at lower energies. The recent discovery of neutrino oscillations has renewed interest in neutrino-nucleus interactions in the sub- to few GeV region. Many atmospheric and accelerator-based neutrino oscillation experiments use interactions of neutrinos in this energy region. Thus, precise knowledge of the interactions is indispensable to improve the accuracy of the neutrino oscillation measurements. This letter presents the result from a search for CC coherent pion production by neutrinos with energies of a few GeV in the KEK to Kamioka (K2K) long-baseline neutrino oscillation experiment. We compare our result specifically with the Rein and Sehgal model [6] 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 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. An almost pure (98%) ν_μ beam with a mean energy of 1.3 GeV [7, 8] is produced by the decay of the secondary particles. The neutrino beam energy spectrum and spatial profile are measured using a set of near neutrino detectors located 300 m downstream from the proton target. The estimated absolute flux has a large uncertainty due to difficulties in the absolute estimation of the primary proton beam intensity, the proton targeting efficiency, and hadron production cross sections. Therefore, the ratio of the CC coherent pion to the total CC cross section is measured, rather than the absolute CC coherent pion cross section. The data used for this analysis were collected with one of the near detectors, the fully active scintillator detector (SciBar), from October 2003 to February 2004, corresponding to 1.7×10^{19} protons on target (POT).

The SciBar detector [9] consists of 14,848 extruded plastic scintillator strips read out by wavelength-shifting fibers and multi-anode PMTs. 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. Each layer consists of two planes to measure horizontal and vertical position. The total size of the detector is $300 \times 300 \times 170$ cm^3 providing a total mass of 15 tons, and the fiducial volume for this analysis is $260 \times 260 \times 135.2$ cm^3 (9.38 tons). The minimum reconstructable track length is 8 cm. A track finding efficiency of more than 99% is achieved for single tracks with a length of more than 10 cm. The track finding efficiency for a second, shorter track is lower than that for single tracks due to overlap with the first track. This efficiency increases with the length of the second track and reaches 90% at a track length of 30 cm. In SciBar, the experimental signatures of CC coherent pion production are 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 the four momenta of the muon and the neutrino, respectively.

The NEUT Monte Carlo (MC) simulation program library [10] is used to simulate neutrino interactions with the nucleus, including CC coherent pion production which is incorporated in the simulation based on the Rein and Sehgal model [6]. From the simulation, the predicted coherent pion production cross section averaged over the K2K neutrino energy spectrum is 2.85×10^{-40}cm^2/nucleon for carbon. The Llewellyn Smith model [11] and the Rein and Sehgal model [12] 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 [13]. For deep inelastic scattering (DIS), we use GRV94 nucleon structure functions [14] with a correction by Bodek and Yang [15], which reduces the cross section by 25% on average for the K2K neutrino energy spectrum. Nuclear effects in the ν-C scattering are taken into account. 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. [16], which agrees well with past experimental data [17]. Pion interactions outside the target nucleus are simulated based on other experimental data [18].

Charged current (CC) candidate 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) [19] located just behind SciBar (SciBar-MRD sample). This criterion imposes a threshold for muon momentum (p_μ) of 450 MeV/c. According to the MC simulation, 98% of the events selected by this 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 determined to be 80 MeV/c and 1.6 degrees, respectively.

For further analysis, events with one or two reconstructed tracks are selected from the SciBar-MRD sample. The two-track events are sub-divided into two categories – QE and non-QE sample – by using kinematic information [20]. The second track, defined as the shorter 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 by 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%.

The CC coherent pion candidates are extracted from the non-QE-pion sample. The dominant background is CC1π interaction with a proton, $\nu_\mu + p \rightarrow \mu^- + \pi^+ + p$, where the proton is below detection threshold or overlapping with other particle tracks. Some of those events are rejected by requiring that the pion-like track goes forward, according to momentum conservation in the 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 deposited 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). Thus, we require the events to have energy deposit less than 7 MeV and no additional hits around the vertex strip. Furthermore, events are required to have a reconstructed q^2 of less than 0.10 $(\mathrm{GeV/c})^2$; this retains about 90% of the simulated coherent pion events. The value of q^2 reconstructed from p_μ and θ_μ under the assumption of QE interaction is denoted q^2_{rec}, and is calculated using

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

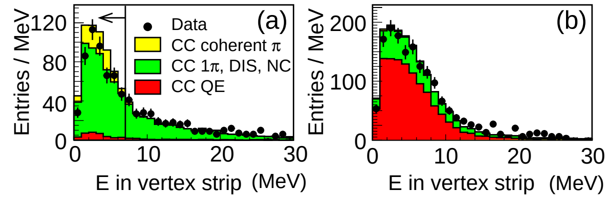

FIG. 1: Energy deposit distribution in the vertex strip for the (a) non-QE pion sample and (b) QE sample. Events with activity less than 7MeV in the sample (a) are selected.

where $M_{p(n)}$ is the proton (neutron) mass, m_μ is the muon mass and V is the nuclear potential set to 27 MeV. The q^2_{rec} for coherent pion production events, which is expected to be very small due to the small scattering angle for muons, is shifted from the true q^2 by 0.008 $(\mathrm{GeV/c})^2$ with a resolution of 0.014 $(\mathrm{GeV/c})^2$.

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

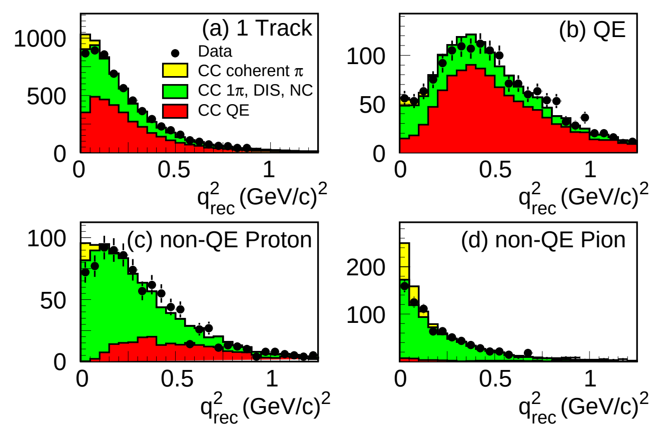

FIG. 2: The q^2_{rec} distributions for the (a) 1track, (b) QE, (c) non-QE-proton, and (d) non-QE-pion samples. Black circles show the observed data and yellow, green, and red histograms show CC coherent pion production, CC-1π/DIS/NC, and QE events estimated by the MC simulation, respectively.

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 signal 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 neutrino energy, estimated using the MC simulation, is shown in Fig. 4(d). The total efficiency is 21.1%. The expected number of background events in the signal 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 from the MC simulation. Hence, no evidence of coherent pion production is found in the present data set.

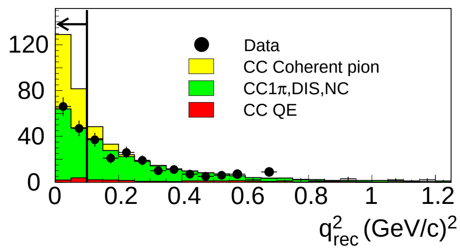

FIG. 3: The reconstructed q^2 distribution in the final sample.

	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 step.

The total number of CC interactions is estimated by using the SciBar-MRD sample. As shown in Table I, 10049 events fall into this category. Based on the MC simulation, the selection efficiency and purity for CC interactions in the sample are estimated to be 56.9% and 98.0%, respectively. The neutrino energy dependence of the CC selection efficiency is shown in Fig. 4(c). By correcting for the efficiency and purity, the total number of CC events is obtained to be $(1.73 \pm 0.02({\rm stat.})) \times 10^4$. We derive the cross section ratio of CC coherent pion production to the total CC interaction to be $(0.04{\pm}0.29({\rm stat.})) \times 10^{-2}$.

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 models. The uncertainty due to nuclear effects is estimated by varying the cross sections of pion absorption and elastic scattering by ±30% based on the

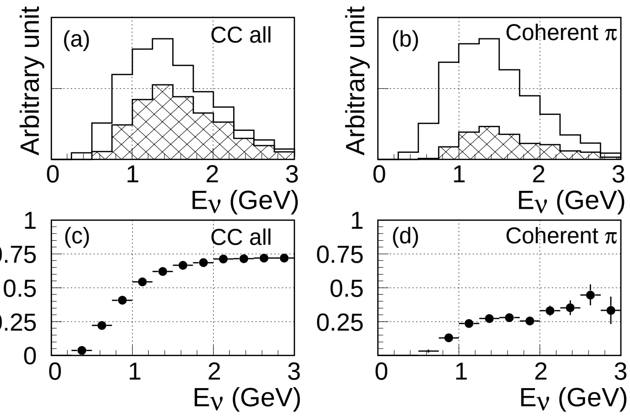

FIG. 4: Top: The neutrino energy spectra for the total CC events and the coherent pion events. The hatched histograms show the selected events. Bottom: The efficiencies as a function of neutrino energy as estimated by the MC simulation.

accuracy of the reference data [17]. 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 amount of correction by ±30%. The $q^2_{\rm rec}$ distribution of the non-QE proton sample (Fig. 2(c)) indicates an additional deficit of background events in the region $q^2_{\rm rec} < 0.10$ $({\rm GeV/c})^2$. CC1π interaction dominates events in this region; its cross section has significant uncertainty due to nuclear effects. We estimate the amount of possible deficit in the same manner as described in [20] 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 $({\rm GeV/c})^2$ is allowed, which is treated conservatively as a systematic uncertainty. 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.

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 uncertainties in the (CC coherent pion)/(total CC interaction) cross section ratio.

The cross section ratio of CC coherent pion production to the total CC interaction is measured to be $(0.04 \pm 0.29({\rm stat.})^{+0.32}_{-0.35}({\rm syst.})) \times 10^{-2}$. Our result is consistent with the non-existence of CC coherent pion production at K2K neutrino beam energies, and hence we set an upper limit on the cross section ratio at 90% C.L. to be:

$$\sigma(\text{CC coherent } \pi)/\sigma(\nu_\mu CC) < 0.60 \times 10^{-2}.$$

The obtained upper limit is inconsistent with the model prediction by Rein and Sehgal of 2.67×10^{-2}. For reference, the total CC cross section is calculated as $1.07 \times 10^{-38}\text{cm}^2/\text{nucleon}$ in the neutrino MC simulation by averaging over K2K neutrino beam energies. There are other models predicting lower cross sections [21–23], but they do not provide the kinematics of pions and it is difficult to test them directly. Assuming the cross section relation $\sigma(\text{CC}) = 2\sigma(\text{NC})$ derived from isospin relations, the result is also inconsistent with the finite cross section for NC interaction reported by the Aachen-Padova group [24] 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 analyzed correspond to 1.7×10^{19} POT 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 CC interaction is derived to be 0.60×10^{-2} at 90% C.L. This result is the first experimental limit for CC coherent pion production by neutrinos with energies of a few GeV.

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[24] H. Faissner *et al.*, Phys. Lett. **B125**, 230 (1983); Their result was obtained with aluminum nuclei. If we assume an $A^{1/3}$ dependence of the cross-section [6] and $\sigma(\text{CC}) = 2\sigma(\text{NC})$, it corresponds to $(3.4 \pm 0.9) \times 10^{-40}\text{cm}^2/\text{nucleon}$ for CC coherent π production in carbon.