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 for neutrino energies from 7 to 100 GeV, while there exists no measurement at lower energies.

The recent discovery of neutrino oscillations has renewed interest in neutrino-nucleus interactions in the sub- to few GeV region. The KEK to Kamioka (K2K) long-baseline neutrino oscillation experiment has reported [7] a significant deficit in the forward scattering events, which limits the prediction accuracy of the neutrino energy spectrum at the far detector. CC coherent pion production is one of the candidate interactions responsible for this deficit, and its study is necessary to improve the accuracy of current and future atmospheric- or accelerator-based neutrino oscillation experiments, which are expected to achieve much improved statistical precision using interactions of neutrinos in the same energy region as K2K.

This Letter presents the result from a search for CC coherent pion production by neutrinos in the K2K 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 and decay to produce an almost pure (98%) ν_μ beam with a mean energy of 1.3 GeV [8]. 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 multianode photomultipliers. 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 $1.3 \times 2.5 \times 300\ \text{cm}^3$ are arranged in 64 layers. Each layer consists of two planes to measure horizontal and vertical position. The total size of the detector is $3.0 \times 3.0 \times 1.7\ \text{m}^3$, while an inner volume of $2.6 \times 2.6 \times 1.35\ \text{m}^3$ (9.38 tons) is used as the fiducial volume to reject incoming particles and obtain a flat efficiency for CC interactions. The minimum reconstructible 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.

The NEUT Monte Carlo (MC) simulation program library [10] is used to simulate neutrino-nucleus interactions. The CC coherent pion production is incorporated in the simulation based on the Rein and Sehgal model [6], which predicts the cross section averaged over the K2K neutrino energy spectrum of $2.85 \times 10^{-40}\ \text{cm}^2/\text{nucleon}$ for carbon. The Llewellyn Smith model [11] and the Rein and Sehgal model [12] are employed for quasielastic (QE) scattering ($\nu_\mu + n \rightarrow \mu^- + p$) and CC single pion ($1\pi$) production ($\nu_\mu + N \rightarrow \mu + N + \pi$), where N is a nucleon, respectively. The axial-vector mass of the nucleon form factor is set to be $1.1\ \text{GeV}/c^2$ for both QE and CC1π interactions [13]. For deep inelastic scattering (DIS), we use Glück, Reya, and Vogt (GRV) nucleon structure functions [14] with a correction by Bodek and Yang [15]. Nuclear effects 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].

For the present analysis, the experimental signatures of CC coherent pion production are the existence of exactly two tracks, both consistent with minimum ionizing particles, and small 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. According to the MC simulation, the dominant background is the CC1π production, where the proton is below threshold or the neutron is invisible.

CC candidate events are selected by requiring that at least one reconstructed track starting in the fiducial volume 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 contribution from ν_e is negligible (<0.4%). 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°, respectively.

From the SciBar-MRD sample, events with two reconstructed tracks are selected. The QE candidate events are rejected by using kinematic information [7]. Events in which the shorter track is identified as protonlike based on dE/dx information (*non-QE-proton* sample) are also rejected to select the *non-QE-pion* sample, which includes the signal candidates. The particle identification capability is verified using cosmic ray muons and the shorter tracks in the QE sample, where the latter provides a proton sample with more than 90% purity. The probability to misidentify a muon track as protonlike 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 background events are suppressed by requiring that the pionlike track goes forward. Even if the additional particles in the background process are not reconstructed as tracks, they can be detected as a large energy deposit or additional hits around the vertex. Figure 1(a) shows a distribution of energy deposited in the vertex strip ($E_{\rm vtx}$) for the non-QE-pion sample. The MC prediction for $E_{\rm vtx}$ is verified with the QE sample, which has no contribution from nonvisible particles, as shown in Fig. 1(b). We require the events to have $E_{\rm vtx}$ less than 7 MeV and no additional hits around the vertex strip.

The value of q^2 reconstructed from p_μ and θ_μ under the assumption of QE interaction is denoted $q^2_{\rm rec}$ and is calculated using

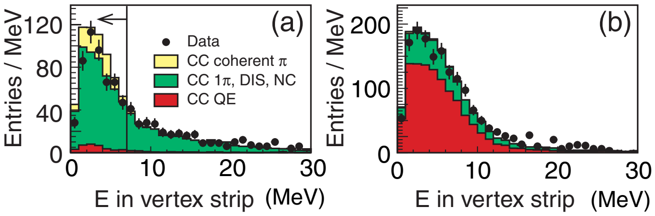

FIG. 1 (color online). Distribution of $E_{\rm vtx}$ for (a) a non-QE-pion sample and (b) a QE sample. Black circles: observed data; histograms: MC expectation with breakdown of interaction modes. The statistical χ^2/DOF in the selected region of (a), indicated by a vertical line, is 30.1/7 (9.8/7) with (without) CC coherent pion production.

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

where $M_{p(n)}$ is the proton (neutron) mass, m_μ is the muon mass, and V is the nuclear potential set to 27 MeV. The $q^2_{\rm rec}$ 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 (GeV/c)^2 with a resolution of 0.014 (GeV/c)^2. Events are required to have a reconstructed q^2 of less than 0.10 (GeV/c)^2.

The background contamination in the final sample is estimated by the MC simulation. In order to constrain the uncertainties, the $q^2_{\rm rec}$ distributions of the data in the region $q^2_{\rm rec} > 0.10$ (GeV/c)^2 are fitted with MC expectations. The one-track sample is used as well as two-track QE, non-QE-proton, and non-QE-pion samples, and these four 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 $q^2_{\rm rec}$ distributions of the data with the MC simulation after the fitting. The χ^2 value

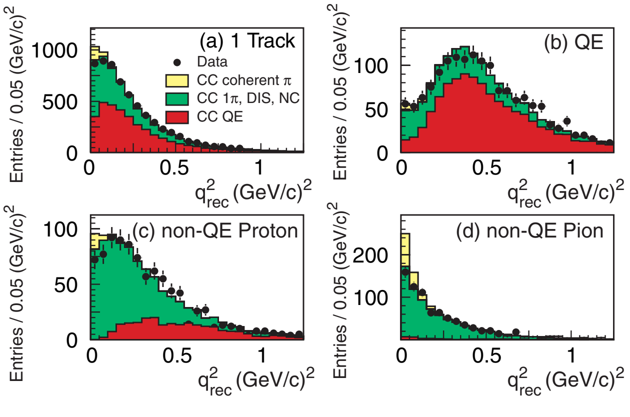

FIG. 2 (color online). The $q^2_{\rm rec}$ distributions for the (a) one-track, (b) QE, (c) non-QE-proton, and (d) non-QE-pion samples. The statistical χ^2/DOF in the region $q^2_{\rm rec} < 0.10$ (GeV/c)^2 of (c) and (d) are 7.2/2 (2.7/2) and 32.3/2 (1.2/2) with (without) CC coherent pion production.

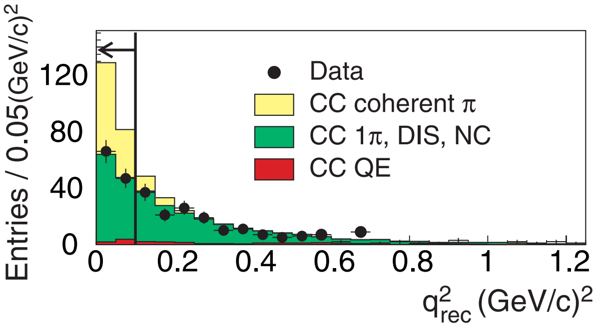

FIG. 3 (color online). The reconstructed q^2 distribution in the final sample.

in the regions with $q^2_{\rm rec} > 0.10\ ({\rm GeV}/c)^2$ at the best fit is 73.2 for 82 degrees of freedom.

Figure 3 shows the $q^2_{\rm rec}$ 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, 113 coherent pion candidates are found. The neutrino energy spectra for coherent pion events and the efficiency as a function of neutrino energy, estimated using the MC simulation, are shown in Figs. 4(a) and 4(c), respectively. 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.

The total number of CC interactions is estimated by using the SciBar-MRD sample. As shown in Table I, 10 049 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 expected neutrino energy spectra and the energy dependence of the selection efficiency for CC events are shown in Figs. 4(b) and 4(d), respectively. 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 $(0.04 \pm 0.29\ ({\rm stat})) \times 10^{-2}$.

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

	Data	Efficiency (%)	Purity (%)
SciBar-MRD	10 049	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
$q^2_{\rm rec} \le 0.10\ ({\rm GeV}/c)^2$	113	21.1	47.1

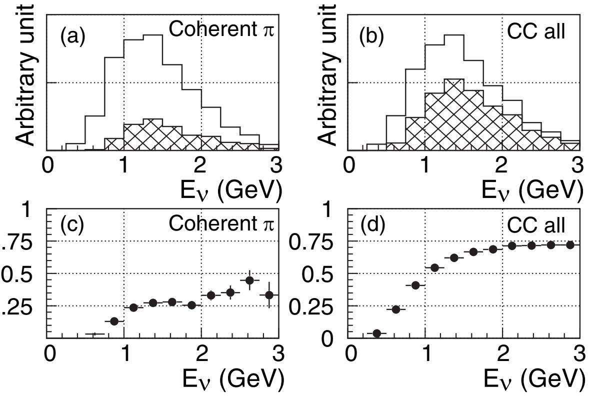

FIG. 4. Top: The neutrino energy spectra for (a) the coherent pion and (b) total CC events. The hatched histograms show the selected events. Bottom: The efficiencies as a function of neutrino energy for (c) the coherent pion and (d) total CC events. All of them are estimated by the MC simulation.

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 accuracy of the reference data [17]. The uncertainties in QE and CC1π interactions are estimated by changing the axial-vector mass by $\pm 0.10\ {\rm GeV}/c^2$ [13]. For DIS, 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 $q^2_{\rm rec} < 0.10\ ({\rm GeV}/c)^2$. CC1$\pi$ 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 Ref. [7] with the one-track, QE, and non-QE-proton samples. We find that a 20% suppression of CC1π events for $q^2_{\rm true} < 0.10\ ({\rm GeV}/c)^2$ is allowed, which varies the cross section ratio by $+0.14 \times 10^{-2}$. This variation is conservatively treated 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

TABLE II. The summary of systematic uncertainties in the (CC coherent pion)/(total CC interaction) cross section ratio.

Error source	Uncertainty of σ ratio ($\times 10^{-2}$)	
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

quenching, and neutrino energy spectrum shape. The total systematic uncertainty on the cross section ratio amounts to $+0.32/-0.35 \times 10^{-2}$.

Our result is consistent with the nonexistence 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.:

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

For reference, the total CC cross section is calculated as 1.07×10^{-38} cm^2/nucleon in the neutrino MC simulation by averaging over K2K neutrino beam energies.

The obtained upper limit is inconsistent with the model prediction by Rein and Sehgal at the level of 2.5 standard deviations. We assign a 35% uncertainty to the theoretical prediction as described in Ref. [6]. In addition, a finite cross section was reported by the Aachen-Padova group for NC coherent pion production with 2 GeV average neutrino energy and with an aluminum target [20]. If we assume an $A^{1/3}$ dependence of the cross section (σ) and $\sigma(\text{CC}) = 2\sigma(\text{NC})$ according to the model of Rein and Sehgal, the discrepancy between the extrapolation from the NC measurement and the present result is as large as 3 standard deviations. 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. Further theoretical work is necessary to construct interaction models which explain these experimental results. The nonexistence of CC coherent pion production has given a solution to the low-q^2 discrepancy observed in K2K. It also reduces the uncertainty on the cross section in the relevant q^2 region, which is crucial for future neutrino oscillation experiments.

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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