Improved measurement of neutral current coherent

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Improved measurement of neutral current coherent π^0 production on carbon in a few-GeV neutrino beam

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The SciBooNE Collaboration reports a measurement of neutral current coherent π^0 production on carbon by a muon neutrino beam with average energy 0.8 GeV. The separation of coherent from inclusive π^0 production has been improved by detecting recoil protons from resonant π^0 production. We measure the ratio of the neutral current coherent π^0 production to total charged current cross sections to be $(1.16 \pm 0.24) \times 10^{-2}$. The ratio of charged current coherent π^+ to neutral current coherent π^0 production is calculated to be $0.14^{+0.30}_{-0.28}$, using our published charged current coherent pion measurement.

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I. INTRODUCTION

Recent measurements of coherent pion production by muon neutrinos at neutrino energies around 1 GeV have inspired significant discussion [1]. In coherent pion production, the neutrino interacts with an entire nucleus; no nucleon recoil occurs and the π^0 tends to be emitted in the forward direction.

For charged current (CC) coherent pion production, both K2K and SciBooNE set limits on the ratio of CC coherent pion production to the total CC cross sections near 1 GeV [2,3], These published upper limits are significantly lower than those predicted by the Rein and Sehgal model [4,5] which is widely used for many neutrino oscillation experiments. Meanwhile, evidence for neutral current (NC) coherent pion production with neutrino energy less than 2 GeV has been reported by the MiniBooNE Collaboration [6]. The SciBooNE Collaboration also reported nonzero NC coherent pion production [7] although the result is only 1.6 standard deviations above zero coherent production. Currently there is no theoretical model which can accommodate all of these recent measurements. Further experimental inputs may help the development of theoretical models.

NC coherent pion production at neutrino energies around 1 GeV is also important for neutrino oscillation experiments as a substantial contribution to NC π^0 production (NC π^0). The largest contribution to NC π^0 is NC resonant pion production, in which the neutrino interacts with a single nucleon in the target nucleus and excites it to a baryon resonance; the resonant decay produces a pion and a nucleon. NC π^0 production is the largest ν_μ-induced background in neutrino experiments searching for $\nu_\mu \rightarrow \nu_e$ oscillations. NC π^0 events cannot be distinguished from ν_e signal events when, for example, one of the two photons associated with $\pi^0 \rightarrow \gamma\gamma$ is not detected.

Both MiniBooNE's and SciBooNE's previous measurements of NC coherent pion production were performed using only emitted π^0 kinematics. However, in addition to the π^0 kinematics, the absence of a recoil nucleon is a clear and less model-dependent feature of coherent pion production. In SciBooNE, detection of the recoil nucleon is possible using the fully active and fine-grained vertex detector, SciBar.

In this paper, we report a measurement of NC coherent π^0 production using a new analysis method in which the lack of recoil nucleons is used to extract the fraction of coherent pions within the inclusive π^0 dataset. SciBooNE's full neutrino data set, corresponding to 0.99×10^{20} protons on target, is used. To simulate coherent π production, the Rein and Sehgal model [4], including lepton mass corrections [5], is used. The axial vector mass M_A and the nuclear radius parameter R_0 used in the model are set to 1.0 GeV$/c^2$ and 1.0 fm, respectively. These are the same values used in previous SciBooNE papers [3,7]. This paper updates our previous result [7], so, not only the coherent π production model but all simulations and the experimental setup used in this analysis are the same as previously described.

II. NC π^0 EVENT SELECTIONS

The SciBooNE detector is comprised of three subsystems: a scintillating bar neutrino vertex detector called SciBar, an electromagnetic calorimeter, and a muon range detector. We use SciBar as the neutrino target as well as the particle tracker for this analysis. SciBar consists of 14 336 polystyrene (C_8H_8) scintillator bars. The scintillators are arranged vertically and horizontally to construct a $3 \times 3 \times 1.7$ m^3 volume with a total mass of 15 tons.

NC π^0 production is observed as two isolated tracks in SciBar due to two gamma rays, coming from the decay of the π^0, converted into two e^+e^- pairs. The background events stem from sources both internal and external to SciBar. Internal backgrounds are neutrino interactions other than NC π^0 (mainly CC) within SciBar. External backgrounds come from neutrino interactions in the material outside of the detector volume (dirt background events) as well as cosmic rays. To reduce these background events, several event selections are performed before extracting coherent π^0s. All selections are identical to those used in the previous analysis [7] and are described in detail there. After event selection, 657 events remain. Subtracting the estimated background of 240 events (202 internal and 38 external) yields 417 signal events. The Monte Carlo (MC) expectation is 368 events. The numbers and distributions obtained by the MC simulation are normalized with the CC data sample [7]. The purity of NC π^0 production after all event selections is estimated to be 61%. The efficiency for NC π^0 production is estimated to be 5.3%. The efficiency for NC coherent π^0 production, incoherent π^0 production[1] with recoil neutron and with recoil proton are estimated to be 7.6%, 6.2%, and 4.5%.[2]

III. COHERENT π^0 EVENT SELECTION

In NC coherent pion production, there is no recoil nucleon in the final state since the π^0 is produced by the neutrino interacting with the whole nucleus. Conversely, a recoiling nucleon should be present in a resonant pion event. To separate the NC coherent π^0 events from the NC resonant π^0 events, recoil protons in the final state are used. The recoil protons are detected by their large energy deposition near the neutrino interaction vertex, so-called vertex activity. We search for the maximum deposited energy in a scintillator strip around the reconstructed vertex, an area of 40 cm $\times$ 40 cm in each view. The choice of 40 cm ($\pm$ 20 cm from the reconstructed vertex) for the area is based on the vertex resolution which is approximately 12 cm for each direction (x, y, and z). A π^0 at typical SciBooNE energies travels, on average, ~20 nm before decaying, so the reconstructed intersection of the gamma tracks is a good estimate of the neutrino interaction vertex. Figure 1 shows the maximum deposited energy distribution after all selections. Most of the coherent π^0 contribution is peaked at zero while the other π^0 events have high energy activity due to recoil protons. Events with

[1]NC incoherent π^0 production is defined as all NC π^0 events except for coherent π^0 production. After event selections, 89% of the incoherent events come from resonant pion production and the rest come from deep inelastic scattering.

[2]High track multiplicity around the neutrino interaction vertex due to the proton recoil can cause misreconstruction of the event.

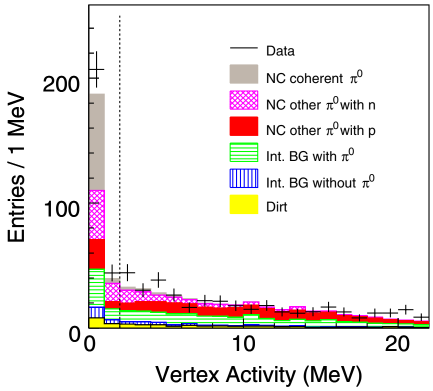

FIG. 1 (color online). Vertex activity after all event selections: the contribution from NC coherent π^0, incoherent NC π^0 with recoil neutrons, incoherent NC π^0 with recoil protons, internal backgrounds with a π^0 in the final state, internal background without a π^0 in the final state and "dirt" background events are shown separately for the MC simulation.

energy deposition greater than 2 MeV are considered to have activity at the vertex. Note that incoherent pion production with a neutron recoil leaves no vertex activity unless the neutron kicks off protons in the region where we search for the energy deposit. Based on our MC simulation, the fraction of proton recoils in all incoherent π^0 events is reduced from 71% in the sample with vertex activity to 35% in the sample without vertex activity.

IV. DATA ANALYSIS

When a neutrino interacts with the entire nucleus, the following relation should be satisfied:

$$\frac{1}{|t|} > R, \tag{1}$$

where t and R are the four-momentum transfer to the target nucleus from the neutrino and the radius of target nucleus, respectively. This means that the cross section decreases rapidly when $1/|t|$ become smaller than R. Using Eq. (1), we can deduce

$$E_{\pi^0}(1 - \cos\theta_{\pi^0}) < \frac{1}{R} \sim 100 \text{ MeV}, \tag{2}$$

following Ref. [8]. In this equation, E_{π^0} and θ_{π^0} are the π^0 energy and direction with respect to the neutrino beam, respectively. From this fact, we can determine the fraction of coherent π^0 production using the reconstructed π^0 kinematic variable $E^{\rm rec}_{\pi^0}(1 - \cos\theta^{\rm rec}_{\pi^0})$, where $E^{\rm rec}_{\pi^0}$ is the reconstructed π^0 energy calculated as the sum of the reconstructed energies of two gamma ray candidates and $\theta^{\rm rec}_{\pi^0}$ is the reconstructed π^0 direction with respect to the neutrino beam axis.

We simultaneously fit two $E^{\rm rec}_{\pi^0}(1 - \cos\theta^{\rm rec}_{\pi^0})$ distributions, with and without the vertex activity, with three templates made by dividing the final MC sample into NC coherent π^0, NC resonant π^0 and background samples. Two parameters, $\mathrm{R_{coh}}$ and $\mathrm{R_{inc}}$ scale the NC coherent π^0 and NC incoherent π^0 templates independently. The background sample is fixed to the value of the MC prediction although the systematic errors on the background prediction are taken into account. The expected number of events in the i-th bin in the $E^{\rm rec}_{\pi^0}(1 - \cos\theta^{\rm rec}_{\pi^0})$ distribution is expressed as

$$N_i^{\rm exp} = \mathrm{R_{coh}} \times N_i^{\rm coh} + \mathrm{R_{inc}} \times N_i^{\rm inc} + N_i^{\rm BG}. \tag{3}$$

The fit minimizes the expression

$$\chi^2 = -2 \ln \frac{f(N^{\rm obs}; N^{\rm exp})}{f(N^{\rm obs}; N^{\rm obs})}, \tag{4}$$

where $N^{\rm obs(exp)}$ represents the observed (expected) number of events in all bins $(N_1^{\rm obs(exp)}, N_2^{\rm obs(exp)}, \ldots, N_N^{\rm obs(exp)})$ and $f(N^{\rm obs}; N^{\rm exp})$ is the Poisson likelihood to find $N^{\rm obs}$ events when $N^{\rm exp}$ events are expected. When the systematic errors for each bin and their correlation expressed with covariance matrix V_{jk} $(j, k = 1, 2, \ldots, N(= 39))$[3] are given, the likelihood is expressed as

$$f(N^{\rm obs}; N^{\rm exp}; V) = A \int \Bigg[\Bigg[\prod_{i=1}^{N} dx_i \frac{x_i^{N_i^{\rm obs}} e^{-x_i}}{N_i^{\rm obs}!}\Bigg] \exp\Bigg[-\frac{1}{2}\sum_{j=1}^{N} \times \sum_{k=1}^{N} (x_j - N_j^{\rm exp}) V_{jk}^{-1} (x_k - N_k^{\rm exp})\Bigg]\Bigg], \tag{5}$$

where A is a normalization constant. The details of the systematic errors and the calculation of the integral are described in Ref. [7]. The result of the fit is

$$\mathrm{R_{coh}} = 0.96 \pm 0.20, \tag{6}$$

$$\mathrm{R_{inc}} = 1.24 \pm 0.13. \tag{7}$$

The $E^{\rm rec}_{\pi^0}(1 - \cos\theta^{\rm rec}_{\pi^0})$ distribution after the fitting is shown in Fig. 2. The χ^2 per degree of freedom, before the fit is $30.8/39 = 0.79$, and it is $26.6/37 = 0.72$ after the fit. Figure 3 shows three contours corresponding to 68%, 90%, and 99% confidence level. The statistical error and all systematic errors are included in the errors of $\mathrm{R_{coh}}$ and $\mathrm{R_{inc}}$. Without the systematic errors, we obtain 0.98 ± 0.18(stat.) and 1.19 ± 0.10(stat.) for $\mathrm{R_{coh}}$ and $\mathrm{R_{inc}}$, respectively. Hence, the uncertainty of the measurement is dominated by the statistical uncertainty. Figs. 4 and 5 show the distributions of the reconstructed π^0 momentum and direction with and without the vertex activity after fitting.

The ratio of the NC coherent π^0 production to the total CC cross sections from the MC prediction based on the

[3]The total number of bins for the two distributions is 40, and there is one bin without entries. We do not include the empty bin in the fit.

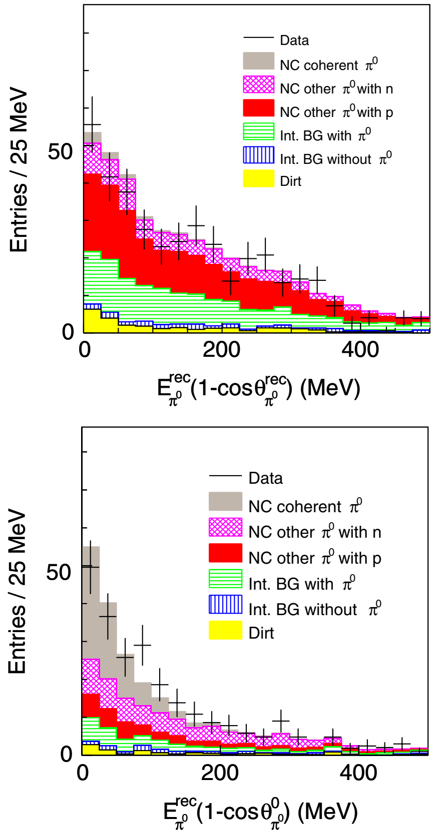

FIG. 2 (color online). The $E^{\rm rec}_{\pi^0}(1-\cos\theta^{\rm rec}_{\pi^0})$ distributions after fitting with (top) and without (bottom) vertex activity.

Rein and Sehgal model is 1.21×10^{-2}. Hence, the cross section ratios are measured to be

$$\frac{\sigma(\mathrm{NCcoh}\pi^0)}{\sigma(\mathrm{CC})} = \mathrm{R_{coh}} \times \frac{\sigma(\mathrm{NCcoh}\pi^0)_{\mathrm{MC}}}{\sigma(\mathrm{CC})_{\mathrm{MC}}},$$
$$= \mathrm{R_{coh}} \times 1.21 \times 10^{-2},$$
$$= (1.16 \pm 0.24) \times 10^{-2}, \qquad (8)$$

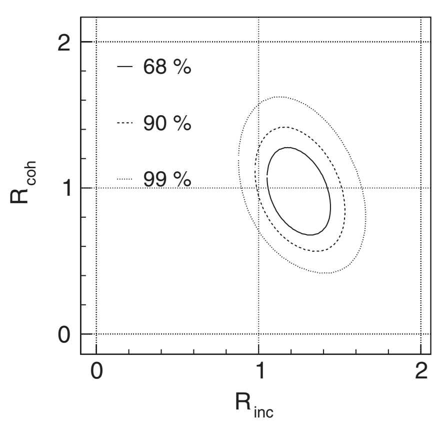

FIG. 3. The contours corresponding to 68%, 90%, and 99% confidence level for the fitted values of the scaling parameters; the number of degrees of freedom is 2.

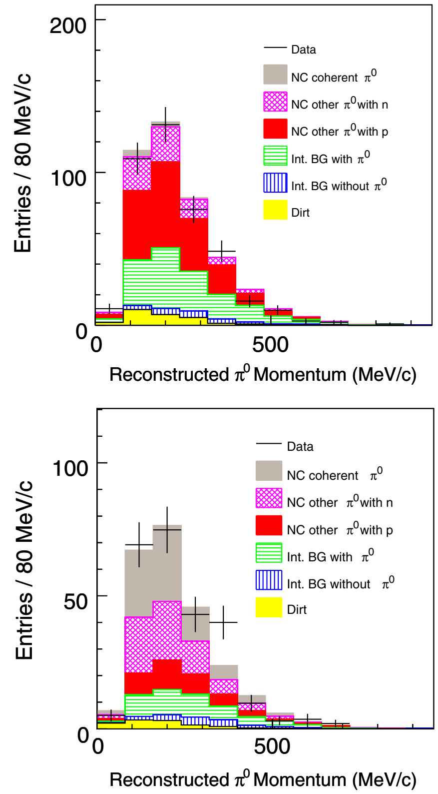

FIG. 4 (color online). Reconstructed π^0 momentum distributions after fitting with the vertex activity (top) and without vertex activity (bottom).

where $\mathrm{R_{coh}}$ is 0.96 ± 0.20. The mean neutrino energy for NC coherent π^0 events in the sample is estimated[4] to be 0.8 GeV. The fractional error of this cross section ratio is 21% while the previous result's fractional error is 60% ($(0.68 \pm 0.41) \times 10^{-2}$). Hence, the result has been improved by a factor of 3 with the new analysis using vertex activity. This result is 5.8 standard deviations above the no coherent production assumption. The measured cross section is also consistent with the MC prediction based on the Rein and Sehgal model [4]. The result is evidence of nonzero coherent pion production via neutral current interactions at mean neutrino energy 0.8 GeV.

[4]In the previous paper [7], the mean neutrino energy was 1.0 GeV despite using the same event sample as this paper. This is due to a different definition of average neutrino energy. In the previous paper, we used mean neutrino energy of all events passing the selection cuts in the MC simulation while, in this paper, we divide the selected neutrino energy distribution by the coherent cross section for each neutrino energy bin before calculating the average of the distribution. The latter method matches SciBooNE's CC coherent result [3]

RAPID COMMUNICATIONS

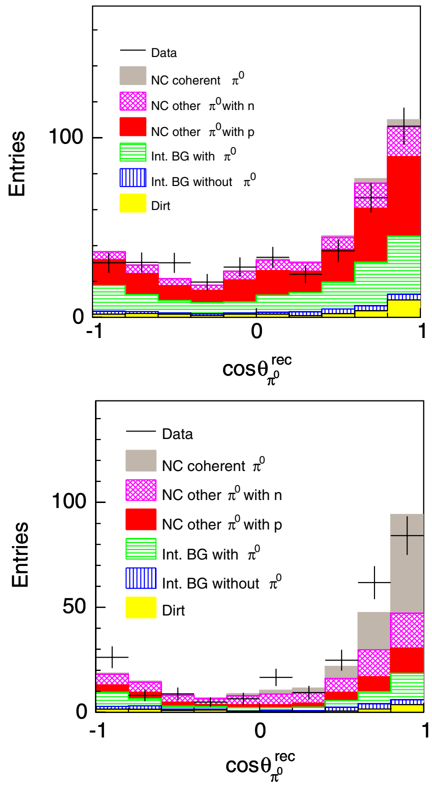

FIG. 5 (color online). The $\cos\theta_{\pi^0}^{\rm rec}$ distributions after fitting with the vertex activity (top) and without vertex activity (bottom).

V. DISCUSSION

A. Comparison with the CC measurement

The SciBooNE Collaboration measured the ratio of the CC coherent pion to total CC production as

$$\frac{\sigma(\mathrm{CCcoh}\pi^+)}{\sigma(\mathrm{CC})} = (0.16 \pm 0.17(\mathrm{stat})^{+0.30}_{-0.27}(\mathrm{sys})) \times 10^{-2}, \tag{9}$$

at 1.1 GeV [3]. According to Eq. (8) and (9), the ratio of CC coherent pion production to NC coherent production is measured to be

$$\frac{\sigma(\mathrm{CCcoh}\pi^+)}{\sigma(\mathrm{NCcoh}\pi^0)} = \frac{\sigma(\mathrm{CCcoh}\pi^+)}{\sigma(\mathrm{CC})} \Big/ \frac{\sigma(\mathrm{NCcoh}\pi^0)}{\sigma(\mathrm{CC})}, = 0.14^{+0.30}_{-0.28}. \tag{10}$$

This result can only be contrasted with predictions, as no other experiment has performed such a ratio measurement in the same neutrino energy range. A detailed comparison of both CC and NC coherent pion production models has been performed in Ref. [9] (see also references therein). The comparison includes MC generators [10] based on the Rein-Sehgal model [4], as well as theoretical models. Both partially conserved axial vector current based models [11] and microscopic models [12] have been considered in the comparison. All models tend to predict a CC/NC coherent pion production ratio of about 2 at high energies ($E_\nu >$ 2 GeV) due to isospin factors. This prediction is in agreement with high energy data ([13], ~7 GeV neutrino energy). As the neutrino energy decreases below 2 GeV, all models predict a reduction in the ratio. The reason is due to muon mass effects, the reduction in the CC phase space factor being the dominant cause. Nevertheless, there is no model we are aware of which can accommodate our measurement of the CC/NC ratio, given that ratio predictions typically lie in the 1.3–1.8 range for SciBooNE neutrino energies. Even if we take into account that the neutrino energy of the CC measurement (1.1 GeV) is higher than that of the NC measurement (0.8 GeV), the corrected ratio ends up with a smaller value because the cross section increases with neutrino energy.

B. Comparison with the MiniBooNE measurement

The MiniBooNE Collaboration measured the ratio of NC coherent pion to NC single π^0 production to be

$$\frac{\sigma(\mathrm{NCcoh}\pi^0)}{\sigma(\mathrm{NCcoh}\pi^0) + \sigma(\mathrm{NCres}\pi^0)} = (19.5 \pm 1.1(\mathrm{stat}) \pm 2.5(\mathrm{sys}))\%, \tag{11}$$

below 2.0 GeV [6], where $\sigma(\mathrm{NCcoh}\pi^0)$ is the cross section for coherent π^0 production and $\sigma(\mathrm{NCres}\pi^0)$ is the cross section for exclusive NC resonant single π^0 production. The qualifier "exclusive" in the latter cross section definition by the MiniBooNE Collaboration refers to a neutrino interaction produced in the resonant channel and with a single π^0 in the final state. Using our fit result ($\mathrm{R_{coh}}$, $\mathrm{R_{inc}}$) shown in Eq. (6), for SciBooNE, the ratio of NC coherent pion to NC single π^0 production is found to be

$$\frac{\mathrm{R_{coh}} \times \sigma(\mathrm{NCcoh}\pi^0)_{\mathrm{MC}}}{\mathrm{R_{coh}} \times \sigma(\mathrm{NCcoh}\pi^0)_{\mathrm{MC}} + \mathrm{R_{inc}} \times \sigma(\mathrm{NCres}\pi^0)_{\mathrm{MC}}} = (17.9 \pm 4.1)\%, \tag{12}$$

where we assume that $\mathrm{R_{inc}}$ scales the NC single resonant π^0 production (although $\mathrm{R_{inc}}$ actually scales all incoherent π^0 production including the multi meson production). In fact, single resonant π^0 production is dominates the incoherent π^0 sample, comprising 81% after event selections. According to Eq. (11) and (12), the SciBooNE measurement agrees with the MiniBooNE result within uncertainties. It should be noted that MiniBooNE uses a CH_2 target and includes diffractive hydrogen scattering in their simulation while SciBooNE uses a CH target and does not include diffractive hydrogen scattering in the simulation. However, the effect of these differences is less than 10%, which is much smaller than the uncertainty of the SciBooNE measurement (23%).

VI. CONCLUSION

In conclusion, we have observed NC coherent π^0 production at mean neutrino energy 0.8 GeV. The ratio of the NC coherent π^0 production to the total CC cross sections is measured to be 1.16×10^{-2} based on the Rein and Sehgal model. Our measurement confirms the previous MiniBooNE result. The ratio of CC coherent π^+ to NC coherent π^0 production is calculated to be $0.14^{+0.30}_{-0.28}$ using SciBooNE's previous CC coherent pion measurement while many models predict 2 as this ratio. We know of no model that can accommodate our measurement of the CC/NC coherent pion production ratio.

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