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Coherent pion production off nuclei at T2K and MiniBooNE energies revisited

E. Hernández,[1] J. Nieves,[2] and M. Valverde[3]

[1]*Departamento de Física Fundamental e IUFFyM,*
Universidad de Salamanca, E-37008 Salamanca, Spain.
[2]*Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia,*
Institutos de Investigación de Paterna, Aptd. 22085, E-46071 Valencia, Spain
[3]*Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki 567-0047, Japan*

As a result of a new improved fit to old bubble chamber data of the dominant axial C_5^A nucleon-to-Delta form factor, and due to the relevance of this form factor for neutrino induced coherent pion production, we re-evaluate our model predictions in Phys. Rev. D **79**, 013002 (2009) for different observables of the latter reaction. Central values for the total cross sections increase by 20%∼30%, while differential cross sections do not change their shape appreciably. Furthermore, we also compute the uncertainties on total, differential and flux averaged cross sections induced by the errors in the determination of C_5^A. Our new results turn out to be compatible within about 1σ with the former ones. Finally, we stress the existing tension between the recent experimental determination of the $\frac{\sigma(\text{CCcoh}\pi^+)}{\sigma(\text{NCcoh}\pi^0)}$ ratio by the SciBooNE Collaboration and the theoretical predictions.

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I. INTRODUCTION

Experimental analyses of neutrino induced coherent pion production generally rely on the Rein–Sehgal (RS) model [1, 2] which is based on the partial conservation of the axial current (PCAC) hypothesis. In the RS model the pion-nucleus coherent cross section is written in terms of the pion-nucleon elastic cross section by means of approximations that are valid for high neutrino energies and small values of the nucleus momentum transfer square and of the lepton momentum transfer square (q^2). As pointed out in Refs. [3, 4], those approximations are less reliable for neutrino energies below/around 1 GeV, light nuclei, like carbon or oxygen, and finite values of q^2. These are the energies and targets used in present and forthcoming neutrino oscillation experiments.

There are other approaches to coherent production that do not rely on PCAC but on microscopic models for pion production at the nucleon level [3, 5–13]. The dominant contribution to the elementary amplitude at low energies is given by the Δ-pole mechanism (Δ excitation and its subsequent decay into πN). Medium effects on the Δ mass and width, final pion distortion, as well as nonlocalities in the pion momentum, are very important and are taken into account in microscopic calculations. Similarly to PCAC models, the process is dominated by the axial part of the weak current and it is thus very sensitive to nucleon-to-Delta axial form factors.

Very recently, the role of nonlocalities in the Δ momentum has also been investigated [12–15]. In Ref. [14] it is claimed that their neglect, the so called, local approximation, leads to an overestimate of the coherent production cross section that can be as large as a factor of 2 for neutrino energies of 500 MeV. Similar results were obtained in Ref. [15]. Final pion distortion and in medium modifications of the Δ properties were not considered, and it was not clear whether those approximations could not affect the results. Final pion distortion and in medium modification of the Δ properties were included in Refs. [12, 13], were nonlocal effects on the Δ momentum were incorporated in the Δ self-energy in the first-order approximation. They also observe a large reduction in the total cross section due to the nonlocal aspects of the Δ propagation in the medium. However, as claimed by the authors of Ref. [13], this that not mean that earlier microscopic calculations [3, 5–11] are wrong, as there Δ nonlocal effects are taken into account in an effective way through the in medium modification of the Δ properties which were fitted to observables.

In the model we developed in Ref. [3], the Δ was treated in the local approximation. However, the modifications of the Δ in medium properties are such that similar models give a good reproduction of pionic atoms and $\pi-$nucleus scattering [16, 17], pion photoproduction [18], pion electroproduction [19], (^{3}He,t) [20] and elastic $\alpha-$proton [21] reactions. We share the claim of the authors of Ref. [13] and we believe this treatment of the Δ, where certainly non-local effects are being effectively (partially) taken into account, is also adequate for neutrino induced reactions. Nevertheless, this interesting issue deserves future investigations.

Our model in Ref. [3] is based on a microscopic model at the nucleon level, described in detail in Ref. [22], that, besides the dominant Δ pole contribution, takes into account background terms required by chiral symmetry. As a result of the inclusion of background terms, we had to re adjust the strength of the dominant Δ pole contribution. The least known ingredients of the model are the axial nucleon-to-Δ transition form factors of which C_5^A, not only gives the largest contribution, but it also controls all other axial form factors if one assumes Adler's model [23] that gives $C_4^A(q^2) = -\frac{C_5^A(q^2)}{4}$, $C_3^A(q^2) = 0$, and PCAC is used to obtain $C_6^A(q^2) = C_5^A(q^2)\frac{M^2}{m_\pi^2 - q^2}$. This strongly suggested to us the readjustment of C_5^A to the experimental data.

Information on pion production off the nucleon comes mainly from two bubble chamber experiments, ANL [24–26] and BNL [27, 28]. Assuming, as proposed in Ref. [29], the q^2 dependence $C_5^A(q^2) = \frac{C_5^A(0)}{(1-q^2/M_{A\Delta}^2)^2}\left(1 - \frac{q^2}{3M_{A\Delta}^2}\right)^{-1}$, we fitted in Ref. [22] the flux-averaged $\nu_\mu p \to \mu^- p\pi^+$ ANL q^2-differential cross section for pion-nucleon invariant masses $W < 1.4$ GeV [24, 26] obtaining $C_5^A(0) = 0.867 \pm 0.075$ and $M_{A\Delta} = 0.985 \pm 0.082$, with a Gaussian correlation coefficient $r = -0.85$ and a $\chi^2/dof = 0.4$. The fitted axial mass was in good agreement with the estimates of about 0.95 GeV and 0.84 GeV given in Refs. [24, 30]. On the other hand, the $C_5^A(0)$ value is some 30% smaller than the prediction obtained from the off diagonal Goldberger-Treiman relation (GTR) that gives $C_5^A(0)\big|_{GTR} = 1.2$. $C_5^A(0)$ is not constrained by chiral perturbation theory (χPT) and lattice calculations are still not conclusive about the size of possible violations of the GTR. For instance, though values for $C_5^A(0)$ as low as 0.9 can be inferred in the chiral limit from the results of Ref. [31], they also predict $C_5^A(0)/\left. C_5^A(0)\right|_{GTR}$ to be greater than one.

Recently, two re-analysis have been carried out trying to make compatible the GTR prediction for $C_5^A(0)$ and ANL data. In Ref. [32], $C_5^A(0)$ is kept to its GTR value and three additional parameters, that control the $C_5^A(q^2)$ fall off, are fitted to the ANL data. Although ANL data are well reproduced, we find the outcome in [32] to be unphysical, as it provides a quite pronounced q^2-dependence giving rise to a too large axial transition radius of around 1.4 fm (further details are discussed in [35]).

A second re-analysis [33] brings in the discussion two interesting points. First that both ANL and BNL data were measured in deuterium, and second, the uncertainties in the neutrino flux normalization. It is claimed in Ref. [33], that the latter could be responsible for BNL total cross sections being systematically larger than ANL ones. In

Ref. [33] the authors do a combined best fit to the ANL and BNL data including deuteron effects, which they evaluate as in Ref. [34], and flux normalization uncertainties, treated as systematic errors, and taken to be 20% for ANL data and 10% for BNL data. With a pure dipole dependence for C_5^A, they found $C_5^A(0) = 1.19 \pm 0.08$, in agreement with the GTR estimate.

The works in Refs. [32, 33] consider only the Δ pole mechanism but ignore the sizable non-resonant contributions which are of special relevance for neutrino energies below 1 GeV. When background terms are considered, the tension between ANL data and the GTR prediction for $C_5^A(0)$ substantially increases as the results in Ref. [22] clearly shows.

In our work in Ref. [36] we have performed a fit to both ANL and BNL data in which: $i)$ We have included the BNL total $\nu_\mu p \to \mu^- p \pi^+$ cross section measurements of Ref. [27]. We have just included the three lowest neutrino energies: 0.65, 0.9 and 1.1 GeV, since there is no cut in the outgoing pion-nucleon invariant mass in the BNL data, and we want to avoid heavier resonances from playing a significant role. We have not used the BNL measurement of the q^2-differential cross section, since it lacked an absolute normalization. $ii)$ We have taken into account deuteron effects, $iii)$ the uncertainties in the neutrino flux normalizations, 20% for ANL and 10% for BNL data, are treated as fully correlated systematic errors, improving thus the simpler treatment adopted in Ref. [33], and finally $iv)$ in some fits, we have relaxed Adler's model constraints, in order to extract some direct information on $C_{3,4}^A(0)$. For simplicity we took $C_5^A(q^2) = \frac{C_5^A(0)}{(1-q^2/M_{A\Delta}^2)^2}$. As in Ref. [33], the consideration of BNL data and flux uncertainties increased the value of $C_5^A(0)$ by about 9%, while strongly reduced the statistical correlations between $C_5^A(0)$ and $M_{A\Delta}$. The inclusion of background terms reduced $C_5^A(0)$ by about 13%, and deuteron effects increased it by about 5%, consistently with the results of [22] and [33, 34], respectively. Fitted data was quite insensitive to $C_{3,4}^A(0)$.

In our most robust fit in Ref. [36] we used Adler's constraints, and we obtained $C_5^A(0) = 1.00 \pm 0.11$, $M_{A\Delta} = 0.93 \pm 0.07\,\text{GeV}$, with a small Gaussian correlation coefficient $r = -0.06$ and a $\chi^2/dof = 0.32$. This violation of the GTR is about 15%, and it is smaller than that suggested in Ref. [22], though it is definitely greater than that claimed in Ref. [33], mostly because in Ref. [33] background terms were not considered. However, the GTR value and the $C_5^A(0)$ above differ in less than 2σ, and the discrepancy is even smaller if Adler's constraints are removed.

These new results are quite relevant for the neutrino induced coherent pion production in nuclei which is a low q^2 dominated reaction. Background term contributions to coherent production largely cancel for symmetric nuclei [3] making the Δ pole mechanism the unique contribution. As the process is dominated by the axial part of the weak current, it is very sensitive to $C_5^A(0)$. Thus, we would expect the results in Ref. [3], based in the determination of $C_5^A(0)$ of Ref. [22], to underestimate cross sections by some 30%. In this work we re-evaluate different pion coherent production observables using our model of Ref. [3] but with the new parameterization and results for C_5^A obtained in Ref. [36]. As the correlation coefficient is small in this case, we shall treat the theoretical errors that derive from the uncertainties in $C_5^A(0)$ and $M_{A\Delta}$ as independent and we shall add them in quadratures.

II.   NEW RESULTS

We start by showing in the left panel of Fig. 1 the differential cross section with respect to the $E_\pi(1 - \cos\theta_\pi)$ variable for neutral current (NC) coherent π^0 production on carbon. E_π is the pion energy in the laboratory frame (LAB) while θ_π is the LAB angle between the pion and the incoming neutrino. The shapes of the distributions are completely similar to the ones we obtained in Ref. [3], but the absolute values increase by some 20%$\sim$ 30% depending on the neutrino energy. This is generally true for other differential cross sections that we do not show here. For the distribution convoluted with the MiniBooNE flux we find an increase in the total cross section of about 29%.

In Table I we show our new predictions for, both NC and charged current (CC) processes, for the K2K [37] and MiniBooNE [39] flux averaged cross sections as well as for the future T2K experiment. In the middle and right panels of Fig. 1, we show some results for T2K and MiniBooNE experiments. In all cases, the flux ϕ is normalized to one. As in Ref. [3], and since we neglect all resonances above the $\Delta(1232)$, we have set up a maximum neutrino energy $(E_{\max}^i)$ in the flux convolution, approximating the convoluted cross section by $\bar{\sigma} \approx \int_{E_{\text{low}}^i}^{E_{\max}^i} dE \phi^i(E)\sigma(E)/\int_{E_{\text{low}}^i}^{E_{\max}^i} dE \phi^i(E)$, where we fixed the upper limit in the integration to $E_{\max} = 1.45\,\text{GeV}$ and 1.34 GeV for CC and NC $\nu_\mu/\bar{\nu}_\mu$ driven processes, respectively. E_{low}^i is the lower flux limit. For the K2K case a threshold of 450 MeV for muon momentum is also implemented [37] and we can to go up to $E_{\max}^{\text{CC,K2K}}=1.8$ GeV. We cover about 90% of the total flux in most of the cases. For the T2K antineutrino flux, we cover just about 65%, and therefore our results are less reliable.

Our central value cross sections increase by some 23%$\sim$30%, while the errors associated to the uncertainties in the $C_5^A(0)$ and $M_{A\Delta}$ determination are of the order of 21%. Our new results are thus compatible with former ones in Ref. [3] within 1σ. Our prediction for the K2K experiment lies more than 1σ below the K2K upper bound, while we still predict an NC MiniBooNE cross section notably smaller than that given in the PhD thesis of J.L. Raaf [38]. Note however, that the MiniBooNE Collaboration has not given an official value for the total coherent cross section

Reaction	Experiment	$\bar{\sigma}$	$\sigma_{\rm exp}$	$E_{\rm max}^i$	$\int_{E_{\rm low}^i}^{E_{\rm max}^i} dE \phi^i(E)\sigma(E)$	$\int_{E_{\rm low}^i}^{E_{\rm max}^i} dE \phi^i(E)$
		$[10^{-40}{\rm cm}^2]$	$[10^{-40}{\rm cm}^2]$	[GeV]	$[10^{-40}{\rm cm}^2]$	
CC $\nu_\mu + {}^{12}$C	K2K	6.1 ± 1.3	< 7.7 [37]	1.80	5.0 ± 1.0	0.82
CC $\nu_\mu + {}^{12}$C	MiniBooNE	3.8 ± 0.8		1.45	3.5 ± 0.7	0.93
CC $\nu_\mu + {}^{12}$C	T2K	3.2 ± 0.6		1.45	2.9 ± 0.6	0.91
CC $\nu_\mu + {}^{16}$O	T2K	3.8 ± 0.8		1.45	3.4 ± 0.7	0.91
NC $\nu_\mu + {}^{12}$C	MiniBooNE	2.6 ± 0.5	$7.7 \pm 1.6 \pm 3.6$ [38]	1.34	2.2 ± 0.5	0.89
NC $\nu_\mu + {}^{12}$C	T2K	2.3 ± 0.5		1.34	2.1 ± 0.5	0.90
NC $\nu_\mu + {}^{16}$O	T2K	2.9 ± 0.6		1.35	2.6 ± 0.6	0.90
CC $\bar{\nu}_\mu + {}^{12}$C	T2K	2.6 ± 0.6		1.45	1.8 ± 0.4	0.67
NC $\bar{\nu}_\mu + {}^{12}$C	T2K	2.0 ± 0.4		1.34	1.3 ± 0.3	0.64

TABLE I. NC/CC ν_μ and $\bar{\nu}_\mu$ coherent pion production total cross sections, with errors, for K2K, MiniBooNE and T2K experiments. In the case of CC K2K, the experimental threshold for the muon momentum $|\vec{k}_\mu| > 450$ MeV is taken into account. Details on the flux convolution are compiled in the last three columns.

yet, and only the ratio coherent/(coherent+incoherent) has been presented [39]. For the future T2K experiment, we now get cross sections of the order $2.4-3.2 \times 10^{-40}{\rm cm}^2$ in carbon and about $2.9-3.8 \times 10^{-40}{\rm cm}^2$ in oxygen.

In Fig. 2 we show new $\nu_\mu/\bar{\nu}$ CC and NC coherent pion production total cross sections off carbon and oxygen targets. As in Ref. [3], we observe sizable corrections to the approximate relation $\sigma_{\rm CC} \approx 2\sigma_{\rm NC}$ for these two isoscalar nuclei in the whole range of $\nu/\bar{\nu}$ energies examined. As pointed out in Refs. [2, 40], this is greatly due to the finite muon mass, and thus the deviations are dramatic at low neutrino energies. In any case, these corrections can not account for the apparent incompatibility among the CC K2K cross section and the NC value quoted in Ref. [38].

The SciBooNE Collaboration has just reported a measurement of NC π^0 production on carbon by a ν_μ beam with average energy $0.8\,{\rm GeV}$ [41]. Based on previous measurements of CC coherent π^+ production [42], they conclude that $\left.\frac{\sigma({\rm CCcoh}\pi^+)}{\sigma({\rm NCcoh}\pi^0)}\right|_{\rm SciBooNE} = 0.14^{+0.30}_{-0.28}$. This result can not be accommodated within our model, or any other present theoretical model, neither microscopic [9–11, 13] nor PCAC based [1, 2, 43, 44]. Theoretically, this ratio cannot be much smaller than 1.4-1.6. For instance, for a carbon target and for a neutrino energy of $0.8\,{\rm GeV}$ we find a value of 1.45 ± 0.03 for that ratio, ten times bigger that the value given by the SciBooNE Collaboration. From the $\nu_\mu + {}^{12}C$ CC and NC MiniBooNE convoluted results shown in Table I, we obtain 1.46 ± 0.03. We believe this huge discrepancy with the SciBooNE result stems form the use in Ref. [41] of the RS model to estimate the ratio between NC coherent π^0 production and the total CC pion production. As clearly shown in Refs. [3, 4], the RS model is not appropriate to describe coherent pion production in the low energy regime of interest for the SciBooNE experiment.
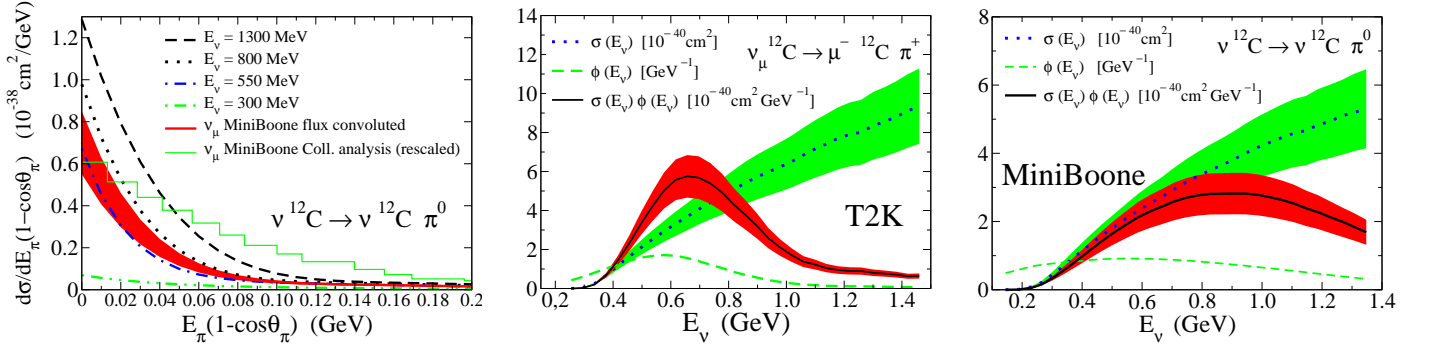

FIG. 1. Left panel: Laboratory $E_\pi(1 - \cos\theta_\pi)$ distribution for the $\nu\,{}^{12}{\rm C} \to \nu\,{}^{12}{\rm C}\pi^0$ reaction, at MiniBooNE energies. We also show, with the corresponding error band, the distribution convoluted with the ν_μ MiniBooNE flux. We display the MiniBooNE published histogram, taken from the right panel of Fig.3 in Ref. [39], conveniently scaled down so that their first bin matches our result at $E_\pi(1 - \cos\theta_\pi) = 0.005$ GeV. Middle and right panels: CC and NC coherent pion production cross sections in carbon (dots). We also show (solid lines) predictions multiplied by the T2K (middle) and MiniBooNE (right) ν_μ energy spectra. The dashed curves curves stand for the T2K and MiniBooNE ν_μ fluxes normalized to one. Error bands are shown for our results.
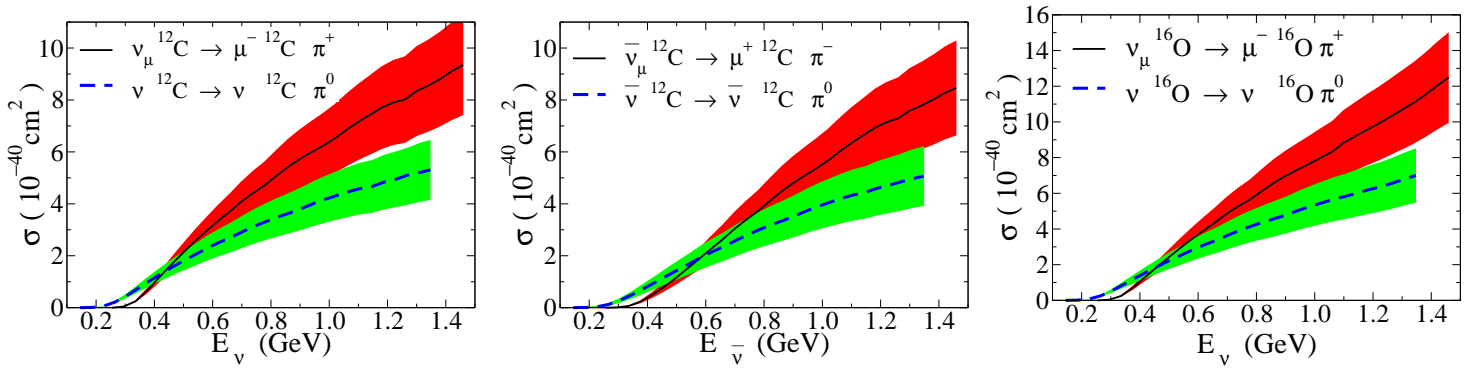
FIG. 2. $\nu_\mu/\bar{\nu}_\mu$ CC and $\nu/\bar{\nu}$ NC coherent pion production from a carbon target (left/middle panel) and ν_μ CC and ν NC coherent pion production from an oxygen target (right panel) as a function of the neutrino/antineutrino energy. Error bands are shown.

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