New determination of the N-$\Delta(1232)$ axial form factors from weak pion production and coherent pion production off nuclei at T2K and MiniBooNE energies revisited

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Abstract. We re-evaluate our model predictions in Phys. Rev. D **79**, 013002 (2009) for different observables in neutrino induced coherent pion production. This comes as a result of the new improved fit to old bubble chamber data of the dominant axial C_5^A nucleon-to-Delta form factor. We find an increase of 20%∼30% in the values for the total cross sections. Uncertainties induced by the errors in the determination of C_5^A are computed. Our new results turn out to be compatible within about 1σ with the former ones. We also stress the existing tension between the recent experimental determination of the $\sigma(\mathrm{CCcoh}\pi^+)/\sigma(\mathrm{NCcoh}\pi^0)$ ratio by the SciBooNE Collaboration and the theoretical predictions.

Keywords: Neutrino reactions, $N\Delta$ weak form factors, coherent pion production
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INTRODUCTION

Pion production by neutrinos in the intermediate energy region is a source of relevant data on hadronic structure. Pions are mainly produced through resonance excitation and these reactions can be used to extract information on nucleon-to-resonance axial transition form factors. Besides, an understanding of these processes is very important in the analysis of neutrino oscillation experiments.

The best available information on pion production by neutrinos off the nucleon comes from old bubble chamber neutrino scattering experiments at ANL [1, 2] and BNL [3, 4]. The latter experiment provides larger cross sections and it has been argued in Ref. [5] that this could be due to neutrino flux uncertainties in both experiments. Both ANL and BNL data were obtained in deuterium[1], and at relatively low energies for which the dominant contribution is given by the Δ pole (ΔP) mechanism: weak excitation of the $\Delta(1232)$ resonance and its subsequent decay into $N\pi$. A convenient parameterization of the $W^+n \to \Delta^+$ vertex is given in terms of eight form-factors: four vector and four axial ($C^A_{3,4,5,6}$) ones. Vector form factors have been determined from the analysis of photo and electro-production data and in our work we use the parameterization of Lalakulich *et al.* [7]. Among the axial form factors the most important contribution comes from C_5^A. The form factor C_6^A, which contribution to the differential cross section vanishes for massless leptons, can be related to C_5^A thanks to the partial conservation of the axial current. Since there are no other theoretical constraints for $C^A_{3,4,5}(q^2)$, they have to be fitted to data. Most analyses, including the ANL and BNL ones, adopt Adler's model [8] where $C_3^A(q^2) = 0$ and $C_4^A(q^2) = -C_5^A(q^2)/4$.

In Ref.[9] we developed a model for weak pion production off the nucleon that, besides the dominant ΔP mechanism, included background terms required by chiral symmetry [2]. Background terms produce quite significant effects and as a result we had to re-fit the $C_5^A(q^2)$ form factor using for that purpose the flux averaged $\nu_\mu p \to \mu^- p\pi^+$ ANL q^2-differential cross section data with final pion-nucleon invariant mass $W < 1.4\,\mathrm{GeV}$. We found $C_5^A(0) = 0.867 \pm 0.075$ [3]. This represents a correction of the order of 30% to the off diagonal Goldberger-Treiman relation (GTR) prediction of $C_5^A(0) \approx 1.2$, the latter being the values used in most theoretical analyses. The consideration of background terms, with the reduced

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[1] Although deuteron effects were evaluated in Ref. [6], where they were estimated to reduce the cross section by 5∼10%, their effect has been neglected in most calculations to date.

[2] Some background terms were already considered in the works of Ref. [10].

[3] Results for the $M_{A\Delta}$ axial mass for this and other fits discussed in this contribution can be found in the quoted references.

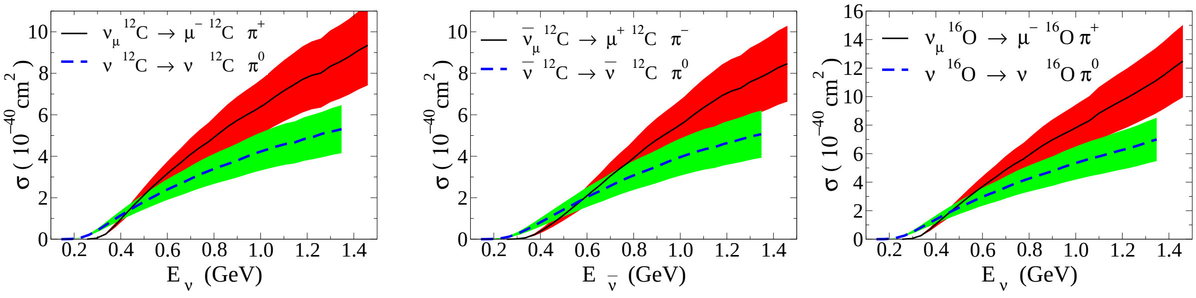

FIGURE 1. $\nu_\mu/\bar\nu_\mu$ CC and $\nu/\bar\nu$ NC CπP cross sections from a carbon target (left & middle panels) and ν_μ CC and ν NC CπP cross sections from an oxygen target (right panel) as a function of the neutrino/antineutrino energy. Error bands are shown. Taken from Ref. [13].

$C_5^A(0)$ value, gave rise to an overall improved description of the data, as compared to the case where only the ΔP mechanism was considered. As mentioned, there is some degree of inconsistency among the ANL and BNL measurements and a good description of BNL data requires a $C_5^A(0)$ value close to the GTR one. The model, with the corresponding medium modifications, was latter applied to coherent pion production (CπP) in nuclei in Ref. [11]. CπP is a low q^2 process which is dominated by the axial part of the weak current. Besides, background term contributions cancel to a large extent for symmetric nuclei, being the ΔP mechanism the unique contribution. CπP is thus very sensitive to $C_5^A(0)$ and our predictions for CπP cross sections in Ref. [11] were notably smaller than previous existing calculations.

Last year Graczyk *et al.* [5] made a combined fit of both ANL and BNL data taking into account deuteron effects, evaluated as in Ref. [6], and, most important, the uncertainties in the neutrino flux normalization, the idea being that ANL and BNL are not incompatible when flux uncertainties are taken into account. Flux uncertainties were 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 work in Ref. [5] considered only the ΔP mechanism but ignored the sizable non-resonant (background) contributions which are of special relevance for neutrino energies below 1 GeV.

In Ref. [12], we have conducted a similar analysis, that besides including ANL and BNL data, deuteron effects and flux uncertainties, it also takes into account the effects of background terms. We now get $C_5^A(0) = 1.00 \pm 0.11$, which is just 2σ away from the GTR value. As a consequence of this new value we expect our results in Ref. [11] to underestimate CπP cross sections by some 30% (corresponding to $[C_5^A(0)|_{new}/C_5^A(0)|_{former}]^2 = [1/0.867]^2 = 1.33$). In this contribution we show some new results, with theoretical uncertainties, for CπP observables obtained with the new $C_5^A(0)$ determination. Further results can be found in Ref. [13].

In Fig. 1 we show new $\nu_\mu/\bar\nu_\mu$ charged current (CC) and $\nu/\bar\nu$ neutral current (NC) CπP cross sections from a carbon target (left & middle panels) and ν_μ CC and ν NC CπP cross sections from an oxygen target. We find an increase in the cross sections by some 20-30%, depending on energy, with respect to our former results in Ref. [11]. This is a consequence of the new $C_5^A(0)$ value . As in Ref. [11], there are large deviations from 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. This is greatly due to the finite muon mass [14, 15], and thus the deviations are dramatic at low neutrino energies.

In Table 1 we show new predictions for both NC and CC processes, for the K2K [16] and MiniBooNE [17] flux averaged cross sections as well as for the T2K experiment. As in Ref. [11], and since we neglect all resonances above the $\Delta(1232)$, we have set up a maximum neutrino energy ($E^i_{\rm max}$) in the flux convolution, of $E_{\rm max} =$ 1.45 GeV and 1.34 GeV for CC and NC $\nu_\mu/\bar\nu_\mu$ driven processes, respectively. For the K2K case a threshold of 450 MeV for muon momentum is also implemented [16] and we can go up to $E_{\rm max}^{\rm CC,K2K}$=1.8 GeV. In this way 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. Central value cross sections increase by some 23%∼30%, while the errors, associated to the uncertainties in the $C_5^A(q^2)$ determination, are of the order of 21%. Our new results are thus compatible with former ones in Ref. [11] 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 [18]. Note however, that this not an official number by the MiniBooNE Collaboration.

Finally we address the issue of the $\frac{\sigma({\rm CCcoh}\pi^+)}{\sigma({\rm NCcoh}\pi^0)}$ ratio. The SciBooNE Collaboration has just reported a measurement of NC coherent π^0 production on carbon by a ν_μ beam with average energy 0.8 GeV [19]. Based on previous measurements of CC coherent π^+ pro-

TABLE 1. 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. Taken from Ref. [13].

Reaction	Experiment	$\bar{\sigma}$ $[10^{-40}\text{cm}^2]$	σ_{exp} $[10^{-40}\text{cm}^2]$	E^i_{max} [GeV]	$\int_{E^i_{\text{low}}}^{E^i_{\text{max}}} dE\phi^i(E)\sigma(E)$ $[10^{-40}\text{cm}^2]$	$\int_{E^i_{\text{low}}}^{E^i_{\text{max}}} dE\phi^i(E)$
CC $\nu_\mu+^{12}\text{C}$	K2K	6.1 ± 1.3	< 7.7 [16]	1.80	5.0 ± 1.0	0.82
CC $\nu_\mu+^{12}\text{C}$	MiniBooNE	3.8 ± 0.8		1.45	3.5 ± 0.7	0.93
CC $\nu_\mu+^{12}\text{C}$	T2K	3.2 ± 0.6		1.45	2.9 ± 0.6	0.91
CC $\nu_\mu+^{16}\text{O}$	T2K	3.8 ± 0.8		1.45	3.4 ± 0.7	0.91
NC $\nu_\mu+^{12}\text{C}$	MiniBooNE	2.6 ± 0.5	$7.7\pm1.6\pm3.6$ [18]	1.34	2.2 ± 0.5	0.89
NC $\nu_\mu+^{12}\text{C}$	T2K	2.3 ± 0.5		1.34	2.1 ± 0.5	0.90
NC $\nu_\mu+^{16}\text{O}$	T2K	2.9 ± 0.6		1.35	2.6 ± 0.6	0.90
CC $\bar{\nu}_\mu+^{12}\text{C}$	T2K	2.6 ± 0.6		1.45	1.8 ± 0.4	0.67
NC $\bar{\nu}_\mu+^{12}\text{C}$	T2K	2.0 ± 0.4		1.34	1.3 ± 0.3	0.64

duction [20], they conclude that $\left.\frac{\sigma(\text{CCcoh}\pi^+)}{\sigma(\text{NCcoh}\pi^0)}\right|_{\text{SciBooNE}} = 0.14^{+0.30}_{-0.28}$. This result can not be accommodated within our model, or any other present theoretical model. Isospin symmetry would predict an exact value of 2 for this ratio in isoscalar nuclei, like carbon or oxygen, provided that 1) vector current is neglected, 2) the muon mass is neglected, and 3) $\cos\theta_C = 1$. The vector current contribution is known to be suppressed by the nuclear form factor (see the discussion after Eq.(5) in Ref. [11]) and the effect of the muon mass can not explain the SciBooNE result for an average neutrino energy of $0.8\,\text{GeV}$. Besides, $\cos\theta_C = 0.974$. Theoretically, one would not expect this ratio to be much smaller than 1.4-1.6. For instance, for a carbon target and for a neutrino energy of $0.8\,\text{GeV}$ 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 $\nu_\mu+^{12}\text{C}$ CC and NC MiniBooNE convoluted results shown in Table 1 we obtain 1.46 ± 0.03. We believe part of this huge discrepancy with the SciBooNE result stems form the use in Ref. [19] of the Rein-Sehgal [21, 14] model to estimate the ratio between NC coherent π^0 production and the total CC pion production. As clearly shown in Refs. [11, 22], the RS model is not appropriate to describe coherent pion production in the low energy regime of interest for the SciBooNE experiment.

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REFERENCES

1. S.J. Barish et al., Phys. Rev. **D19**, 2521 (1979).
2. G.M. Radecky et al., Phys. Rev. **D25**, 1161 (1982).
3. T. Kitagaki et al., Phys. Rev. **D34**, 2554 (1986).
4. T. Kitagaki *et al.*, Phys. Rev **D42**, 1331 (1990).
5. K. M. Graczyk, D. Kielczewska, P. Przewlocki and J. T. Sobczyk, Phys. Rev. D **80**, 093001 (2009).
6. L. Alvarez-Ruso, S. K. Singh and M. J. Vicente Vacas, Phys. Rev. C **59**, 3386 (1999).
7. O. Lalakulich, E. A. Paschos and G. Piranishvili, Phys. Rev. D **74**, 014009 (2006).
8. S.L. Adler, Ann. Phys. **50** (1968) 189; J. Bijtebier, Nucl. Phys. **B21** (1970) 158.
9. E. Hernandez, J. Nieves and M. Valverde, Phys. Rev. D **76**, 033005 (2007).
10. G.L. Fogli and G. Nardulli, Nucl. Phys. **B160** (1979) 116; G.L. Fogli and G. Nardulli, Nucl. Phys. **B165** (1980) 162; T. Sato, D. Uno and T.S.H. Lee, Phys. Rev. **C67** (2003) 065201.
11. J. E. Amaro, E. Hernandez, J. Nieves and M. Valverde, Phys. Rev. D **79**, 013002 (2009).
12. E. Hernandez, J. Nieves, M. Valverde and M. J. Vicente-Vacas, Phys. Rev. D **81**, 085046 (2010).
13. E. Hernandez, J. Nieves and M. Valverde, Phys. Rev. D **82**, 077303 (2010).
14. D. Rein and L. M. Sehgal, Phys. Lett. B **657**, 207 (2007).
15. C. Berger and L. M. Sehgal, Phys. Rev. D **76**, 113004 (2007); erratum Ibid. **77**, 059901(E) (2008).
16. M. Hasegawa *et al.* [K2K Collaboration], Phys. Rev. Lett. **95**, 252301 (2005).
17. A. A. Aguilar-Arevalo *et al.* [MiniBooNE Collaboration], Phys. Lett. B **664**, 41 (2008).
18. J.L. Raaf, FERMILAB-THESIS-2007-20 (2005).
19. Y. Kurimoto *et al.* [SciBooNE Collaboration], Phys. Rev. D **81**, 111102 (2010).
20. K. Hiraide *et al.* [SciBooNE Collaboration], Phys. Rev. D **78**, 112004 (2008).
21. D. Rein and L. M. Sehgal, Nuc. Phys. B **223**, 29 (1983).
22. E. Hernandez, J. Nieves and M. J. Vicente-Vacas, Phys. Rev. D **80**, 013003 (2009).