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C_5^A FORM FACTOR FROM ANL EXPERIMENT*

Krzysztof M. Graczyk[a], Danuta Kiełczewska[b], Jan T. Sobczyk[a]

[a]Institute of Theoretical Physics, University of Wrocław
pl. M. Borna 9, 50-204 Wrocław, Poland

[b]The A. Soltan Institute for Nuclear Studies
Hoża 69, 00-681 Warsaw, Poland

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$C_5^A(Q^2)$ axial form factor is extracted from the ANL neutrino–deuteron scattering data with deuteron structure effects taken into consideration. The best fit of the $C_5^A(Q^2)$ axial form factor is obtained assuming dipole parametrization with $C_5^A(0) = 1.13 \pm 0.15$ and $M_A = 0.94 \pm 0.08$ GeV.

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1. Introduction

A knowledge of the cross-sections for single pion production in neutrino–nucleon scattering is an important ingredient of the long base-line oscillation experiment analyses (see experiments: K2K [1] and T2K [2]). In particular, prediction of the cross-sections for $1\pi^0$ production in neutral current neutrino–nucleon scattering has great importance for the estimation of the background for observation of the $\nu_\mu \to \nu_e$ neutrino oscillation. The reason is that the signal of π^0 decay into two photons with the electron shower in the detector can be misleading.

More than twenty years ago two bubble chamber experiments: 12 ft detector at Argonne National Laboratory (ANL) [3, 4] and 7 ft detector at Brookhaven National Laboratory (BNL) [5] had collected enough data to investigate the W, Q^2 and energy dependence of the differential and total cross-sections for neutrino–deuteron scattering. The ANL and BNL experimental measurements can still serve as an important source of information about cross-sections for quasi-elastic and single pion production in neutrino

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scattering. The nuclear effects (deuteron structure corrections) are relatively easy to consider, therefore analysis of these data allows to study neutrino–nucleon reactions.

In this paper a part of the re-analysis [6] of the neutrino–deuteron scattering data is presented. We re-examine the single pion production in neutrino deuteron interactions. Our aim is re-extraction of the $C_5^A(Q^2)$ axial form factor from the 1π data. In this article we discuss only the data collected at Argonne National Laboratory. In the longer contribution [6] simultaneous analysis of both ANL and BNL data is described.

The presentation is organized as follows: in Section 2 the model for $\Delta(1232)$ excitation is shortly introduced. Section 3 contains description of the ANL data and details of the statistical analysis. Section 4 includes our final results and conclusions.

2. Single pion production

We consider the following process:

$$\nu(k) + p(p) \to \mu^-(k') + \Delta^{++}(p')\{\to \pi^+(l) + p(r)\}\,. \tag{1}$$

By the k and k' the neutrino and muon four-momenta are denoted. The incoming nucleon momentum is denoted by p, while l and r are the final pion and proton momenta. The four momentum transfer is defined as follows $Q^2 = -(k-k')^2$. The total hadronic momentum is $p' = l + r$.

One of the simplest way to describe the above reaction is to apply the Adler–Rarita–Schwinger formalism [7]. In this description the scattering amplitude is given by the contraction of the lepton $j^{\mu}_{\rm lep}$ with the hadronic $\langle \Delta^{++}, p'|\, \mathcal{J}^{CC}_{\mu}\, |p\rangle$ currents. The hadronic current has Vector–Axial structure, where the vector contribution is modeled by three unknown vector form factors C_3^V, C_4^V and C_5^V. For these form factors we apply recent fits from Ref. [8].

In general, the axial contribution to the hadronic current is given by four form factors, however, additional constrains, motivated by Adler model [9] and PCAC hypothesis, reduce the number of unknown functions to the one: $C_5^A(Q^2)$.

In the present analysis we consider the dipole parametrization of the $C_5^A(Q^2)$ axial form factor:

$$C_5^A(Q^2) = C_5^A(0)\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}\,. \tag{2}$$

The axial mass M_A is a parameter to fit. We distinguish two fit cases:

(i) the value of $C_5^A(0)$ is established by PCAC and equals 1.15 [10];

(ii) $C_5^A(0)$ is treated as a free parameter.

3. Re-analysis of the ANL data

A subject of our analysis is the differential cross-section data

$$\frac{d\sigma}{dQ^2}\left(Q_i^2\right) \equiv \sigma_{\rm exp}\left(Q_i^2\right) , \tag{3}$$

which was published in Ref. [4]. In the reaction (1) the dominant contribution comes from the excitation of the $\Delta(1232)$ resonance. The nonresonant background can be neglected.

The proper analysis of the (1) process requires taking into consideration the deuteron structure effects. In this work we follow the approach proposed in Ref. [11]. From the practical point of view, in order to obtain the differential cross-section for neutrino–deuteron scattering, we multiply neutrino–*free nucleon* $\sigma(Q_i^2)$ formula by

$$R\left(Q^2\right) = \frac{\sigma(\nu d \to \mu^- \pi^+ p + n)}{\sigma(\nu p \to \mu^- \pi^+ p)}$$

correcting function. It is obtained from Ref. [11] (for more details see Ref. [6]).

To analyze the data we apply the standard χ^2 approach. Besides statistical and non-correlated systematical uncertainties in each Q_i^2 bin, we take into account the overall uncertainty of the neutrino beam. It introduces to the standard χ^2 formula an additional normalization term:

$$\chi^2 = \sum_{i=1}^{n}\left(\frac{\sigma_{\rm th}(Q_i^2) - p\sigma_{\rm ex}\left(Q_i^2\right)}{p\Delta\sigma_i}\right)^2 + \left(\frac{p-1}{r}\right)^2 , \tag{4}$$

where $\sigma_{\rm th}(Q_i^2)$ and $\sigma_{\rm ex}$ are the theoretical and experimental values of the differential cross-sections. $\Delta\sigma_i$ denotes error in each Q_i^2 bin. r is the uncertainty of the neutrino flux and p is the normalization parameter which is going to be fitted.

In order to compute the theoretical values of the cross-section the following kinematical cuts are imposed: for the neutrino energy $E \in (0.5, 6)$ GeV, and for the hadronic invariant mass $W < 1.4$ GeV. The data covers the range in Q^2 from $Q^2 = 0.01\,{\rm GeV}^2$ to $Q^2 = 1\,{\rm GeV}^2$.

The theoretical formula for the differential cross-section in a given Q^2 bin is the following:

$$\sigma_{\rm th}(Q_i^2) = \int\limits_{Q^2_{i,\rm lo}}^{Q^2_{i,\rm up}} \frac{dQ^2}{\Delta Q_i^2} \int\limits_{E_{\rm lo}}^{E_{\rm up}} \frac{dE}{\Psi} \Phi(E) \int\limits_{M+m_\pi}^{1.4\,\rm GeV} dW \sigma_{\rm th}(E, Q^2, W)\,, \quad (5)$$

with

$$Q^2_{i,\rm lo} = Q_i^2 - \Delta Q_i^2/2\,, \qquad Q^2_{i,\rm up} = Q_i^2 + \Delta Q_i^2/2\,,$$

$$\Psi = \int\limits_{E_{\rm lo}}^{E_{\rm up}} dE \varPhi_{\rm ANL}(E)\,, \quad (6)$$

where $E_{\rm lo} = 0.5\,\rm GeV$ and $E_{\rm up} = 6\,\rm GeV$.

As it was discussed in Ref. [4] the normalization uncertainty of the total cross-section, due to the lack of knowledge about the flux is estimated to be 15% for $E \in (0.5, 1.5)\,\rm GeV$ and 25% for $E > 1.5\,\rm GeV$. Therefore, in our discussion, we assume the average overall normalization uncertainty to be 20%, $r = 0.20$.

4. Results and conclusions

The results of our fitting procedure are shown in Table I . In the analysis we consider four different cases. We start the fitting procedure without accounting deuteron correction. The results are shown in the first two rows of Table I. Then the deuteron corrections are taken into consideration (look at the third and fourth rows of Table I).

TABLE I

The obtained numbers for $C_5^A(Q^2)$ and M_A resulting from the fitting procedure.

	M_A [GeV]	$C_5^A(0)$	p	χ^2/NDF
Free target	0.948 ± 0.074	—	1.15 ± 0.09	1.50/7
Free target	0.939 ± 0.082	1.04 ± 0.14	1.02 ± 0.19	0.94/6
Deuteron	0.937 ± 0.075	—	1.03 ± 0.09	0.81/7
Deuteron	0.936 ± 0.077	1.13±0.15	1.02 ± 0.19	0.80/6

The comparison of our fits with the ANL data is shown in Fig. 1, where both the differential and total cross-sections are plotted.

Our final result (with deuteron effects) is

$$M_A = 0.936 \pm 0.077\,\rm GeV\,, \qquad C_5^A(0) = 1.13 \pm 0.15\,. \quad (7)$$

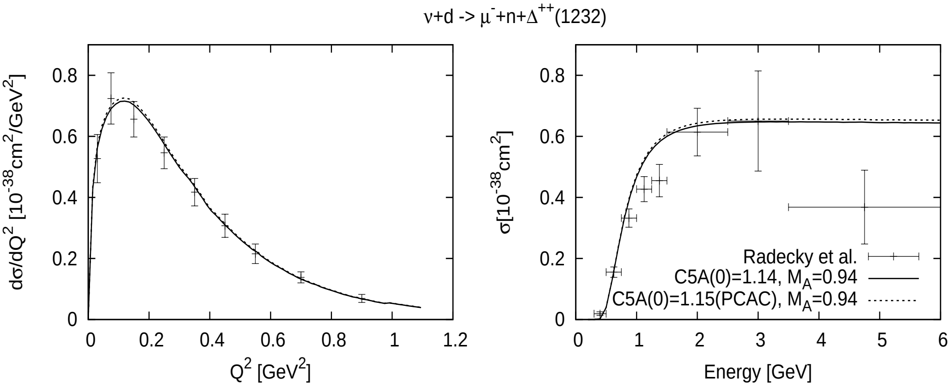

Fig. 1. The differential (left panel) and total (right panel) cross-sections for $\nu + d \to \mu^- + n + \Delta^{++}(1232)$ reaction measured at ANL experiment. The experimental points are taken from [4]. The solid line denotes cross-section computed with $C_5^A(0) = 1.13$ and $M_A = 0.936\,\mathrm{GeV}$. The dashed line represents cross-section computed with $C_5^A(0) = 1.15$ (fixed) and $M_A = 0.937\,\mathrm{GeV}$. Both fits were obtained with accounting deuteron structure effects. The cut $W < 1.4\,\mathrm{GeV}$ on hadronic invariant mass is imposed. The normalization parameter is $p = 1$. In the left panel in order to compute cross-section the deuteron structure correction is imposed.

As it can be noticed for all fits the obtained values of χ^2/NDF (NDF — number of degrees of freedom) are very good. We observe that the axial mass, which is responsible for the shape of $d\sigma/dQ^2$, is not affected by the deuteron corrections. The deuteron nuclear effects affect mainly the normalization of the cross-section, therefore they are compensated by the normalization parameter p.

The largest suppression of the $\sigma(Q^2)$, due to deuteron effects appears in low-Q^2 (below $0.1\,\mathrm{GeV}^2$). That is why the fit of $C_5^A(0)$ without deuteron correction is relatively low (≈ 1.04). When the deuteron effects are accounted the obtained value is ≈ 1.13 which is very close to the PCAC value. However, both results for $C_5^A(0)$ are always in agreement with the PCAC value.

The fits obtained for the ANL data turns out to be quite similar to those obtained from the simultaneous fit to both the ANL and BNL data. The full presentation of this analysis will be published in Ref. [6].

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REFERENCES

[1] M.H. Ahn, *Phys. Rev.* **D74**, 072003 (2006).

[2] http://jnusrv01.kek.jp/public/t2k/.

[3] S.J. Barish *et al., Phys. Rev.* **D16**, 3103 (1977); S.J. Barish *et al., Phys. Rev.* **D19**, 2521 (1979);

[4] G.M. Radecky *et al., Phys. Rev.* **D25**, 1161 (1982).

[5] T. Kitagaki *et al., Phys. Rev.* **D34**, 2554 (1986); T. Kitagaki *et al., Phys. Rev.* **D42**, 1331 (1990).

[6] K.M. Graczyk, D. Kiełczewska, P. Przewłocki, J.T. Sobczyk, in preparation.

[7] P.A. Schreiner, F. von Hippel, *Nucl. Phys.* **B58**, 333 (1973).

[8] O. Lalakulich, E.A. Paschos, G. Piranishvili, *Phys. Rev.* **D74**, 014009 (2006).

[9] S.L. Adler, *Ann. Phys.* **50**, 189 (1968).

[10] D. Barquilla-Cano, A.J. Buchmann, E. Hernandez, *Phys. Rev.* **C75**, 065203 (2007) [Erratum **C77**, 019903 (2008)].

[11] L. Alvarez-Ruso, S.K. Singh, M.J. Vicente Vacas, *Phys. Rev.* **C59**, 3386 (1999).