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Special Issue
Neutrino Insights: Peering into the Subatomic Universe

Edited by
Dr. Guillermo D. Megias

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https://doi.org/10.3390/universe10100399 universe

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Neutral-Current Single π^0 Production on Argon

Marco Martini [1,2,*], Magda Ericson [3,4] and Guy Chanfray [3]

1 IPSA-DRII , 63 boulevard de Brandebourg, F-94200 Ivry-sur-Seine, France
2 Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), UMR 7585, CNRS/IN2P3, Sorbonne Université, F-75005 Paris, France
3 Institut de Physique des 2 Infinis de Lyon (IP2I), UMR 5822, CNRS/IN2P3, Université Claude Bernard Lyon 1, Université de Lyon, F-69622 Villeurbanne, France; mericson@cern.ch (M.E.); g.chanfray@ipnl.in2p3.fr (G.C.)
4 Theory Division, CERN, CH-12111 Geneva, Switzerland
* Correspondence: marco.martini@ipsa.fr

Abstract: We interpret the recent MicroBooNE data on neutral-current single π^0 production on argon with the hypothesis that this process occurs via Delta excitation. We calculate the flux-integrated total cross section with our RPA-based model which allows for a simultaneous description of Delta-mediated resonant and coherent pion production. We also discuss the ratio between the two exclusive measurements with one proton and zero protons in the final state.

Keywords: neutrino–nucleus cross sections; pion production; Delta resonance

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Citation: Martini, M.; Ericson, M.; Chanfray, G. Neutral-Current Single π^0 Production on Argon. *Universe* **2024**, *10*, 399. https://doi.org/10.3390/universe10100399

Academic Editor: Guillermo D. Megias

Received: 27 August 2024
Revised: 2 October 2024
Accepted: 9 October 2024
Published: 16 October 2024

1. Introduction

The MicroBooNE collaboration has recently performed a measurement of single π_0 production by neutral-current neutrino scattering on argon with either one proton or zero protons in the final state [1]. They also measured the total neutral-current $1\pi_0$ production cross section. This measurement offers an opportunity to test the assumption that at low or moderate neutrino energies ($E_\nu < 1$ GeV), pion production occurs via Delta excitation, as in our model [2].

2. Theoretical Approach and Results

Our theoretical approach is based on nuclear response functions treated in Random Phase Approximation (RPA) and allows for a unified description of several channels: quasielastic, multinucleon knock-out, resonant and coherent one-pion production. All the theoretical details, as well as several charged-current and neutral-current cross sections in the different channels, are given in ref. [2], to which we refer the reader. Here, we remind the reader that the one-pion production is treated via the Delta (1232) resonance (Δ) excitation only. This is a good approximation up to $E_\nu = 1.5$ GeV, as shown in ref. [3]. The incoherent and coherent contributions to $1\pi^0$ production are both included in our evaluations and are obtained by summing the RPA chain as depicted in Figure 1. We stress that our approach is based on the semiclassical description of the nuclei, with the local density approximation. This is one of the most effective approaches to evaluate the cross sections in the case of accelerator-based neutrino experiments where broad neutrino-fluxes of several hundreds of MeV wash out low-energy nuclear structure effects for quasielastic exciations and beyond, as illustrated, for example, in ref. [4]. Examples of other calculations based on local density approximation for one-pion production are the ones of refs. [3,5,6]. For our calculations, we assume, as in our previous paper on argon [7], that the ^{40}Ca and ^{40}Ar density profiles are identical, since ^{40}Ca and ^{40}Ar have the same total nucleon number. Moreover, we assume that the proton and neutron density profiles of ^{40}Ar are also the ones of ^{40}Ca. This is a good approximation, as one can observe by comparing the ^{40}Ar and ^{40}Ca experimental charge densities [8], available on the website [9], or by comparing the theoretical neutron and proton matter densities obtained via the Hartree–Fock–Bogoliubov approach of ref. [10], available on the website [11].

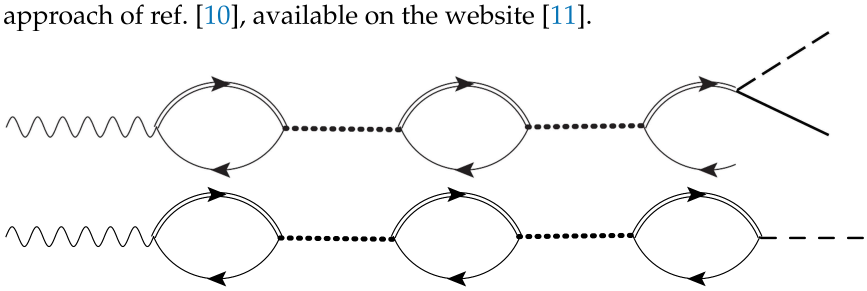

Figure 1. Diagrammatic RPA representation of the incoherent (**upper** figure) and coherent (**lower** figure) one-pion production process. The wiggly line represents the external probe. Double lines correspond to the propagation of Delta, solid lines correspond to the propagation of a nucleon hole (and of a nucleon), thick dotted lines correspond to the Delta-hole interaction and the dashed line represents the pion.

In the nucleus, the two elementary neutral-current reactions involving Delta excitations are:

$$\nu + p \quad \rightarrow \quad \nu + \Delta^{+}, \tag{1}$$
$$\nu + n \quad \rightarrow \quad \nu + \Delta^{0}. \tag{2}$$

The branching ratios for the Delta decay are as follows [12]:

$$\Delta^{+} \quad \rightarrow \quad \frac{2}{3}\pi^{0}p + \frac{1}{3}\pi^{+}n, \tag{3}$$
$$\Delta^{0} \quad \rightarrow \quad \frac{2}{3}\pi^{0}n + \frac{1}{3}\pi^{-}p. \tag{4}$$

Notice that the two branching ratios involving $1\pi^0$ production are identical, hence the incoherent $1\pi^0$ production is simply obtained by multiplying the total Delta-mediated cross section by the factor 2/3. Therefore, the total incoherent $1\pi^0$ production cross sections for ^{40}Ca and ^{40}Ar coincide when final-state interactions are ignored, which is the case for our description. For the coherent channel, the neutral current necessarily produces a π^0 and no isospin reduction factor applies. In our evaluation of pion cross sections, the Delta propagator, calculated in RPA scheme, is dressed by one particle–one hole (1p-1h), 2p-2h and 3p-3h states, according to the prescription of Oset and Salcedo [13].

In order to evaluate the total MicroBooNE flux-integrated NC$1\pi^0$ cross section, we consider the ν_μ, ν_e, $\bar{\nu}_\mu$ and $\bar{\nu}_e$ MicroBooNE fluxes ϕ. We remind the reader that, as mentioned in ref. [1], the total MicroBooNE beam is composed of 93.7% ν_μ, 5.8% $\bar{\nu}_\mu$, and 0.5% $\nu_e/\bar{\nu}_e$, with a mean energy $\langle E_\nu \rangle = 804$ MeV. The total cross section is hence obtained as a combination of flux-integrated neutrino and antineutrino cross sections according to the following formula:

$$\sigma_{\mathrm{NC}1\pi^0} = \frac{\int dE_\nu \sigma^{\nu}_{\mathrm{NC}1\pi^0}(E_\nu)\left[\phi_{\nu_\mu}(E_\nu) + \phi_{\nu_e}(E_\nu)\right] + \int dE_\nu \sigma^{\bar{\nu}}_{\mathrm{NC}1\pi^0}(E_\nu)\left[\phi_{\bar{\nu}_\mu}(E_\nu) + \phi_{\bar{\nu}_e}(E_\nu)\right]}{\int dE_\nu \left[\phi_{\nu_\mu}(E_\nu) + \phi_{\nu_e}(E_\nu) + \phi_{\bar{\nu}_\mu}(E_\nu) + \phi_{\bar{\nu}_e}(E_\nu)\right]}. \tag{5}$$

Our RPA calculation leads to:

$$\sigma_{\mathrm{NC}1\pi^0} = 1.58\ 10^{-38}\ \mathrm{cm}^2 \quad \mathrm{RPA},$$

a value compatible with the MicroBooNE measurement:

$$\sigma_{\mathrm{NC}1\pi^0} = (1.243 \pm 0.185 \pm 0.076)\ 10^{-38}\ \mathrm{cm}^2 \quad \mathrm{MicroBooNE}.$$

Our number is about 30 percent above the experimental one. Our overestimation is likely due to the absence in our description of final-state interactions (pion absorption and charge exchange) for the emitted pion in its way out from the nucleus. Their inclusion is expected to reduce the results at the level of $\simeq$15%–30% [6,14].

It is interesting to compare our predictions also to the MiniBooNE NC1π^0 cross section measurement on CH_2 [15] and to compare the MicroBooNE and MiniBooNE experimental cross section *per nucleon*, as already carried out in the MicroBooNE paper [1]. For this purpose, we show in Figure 2 these cross sections, compared to our results, as well as to the GENIE Monte Carlo prediction [16] used by MicroBooNE. Further details on our results can be found in Table 1, where the separated coherent and incoherent NC1π^0 cross sections on ^{40}Ar, ^{12}C and protons are given. We stress that in the case of MiniBooNE, our calculations are performed by considering only the MiniBooNE ν_μ flux with a mean energy $\langle E_\nu \rangle = 808$ MeV. It appears that, as for the GENIE predictions, our evaluations overestimate the MicroBooNE ones and underestimate the MiniBooNE ones. We mention that in the past we found an agreement between our calculation and the CC1π^+ measurement of MiniBooNE [17]. We remark also that the MiniBooNE experimental result is not only larger than the MicroBooNE one, but is even larger than the cross section prediction on the proton, which is surprising since nuclear effects (in-medium Delta width, RPA, pion FSI) reduce the cross sections. The difference between MicroBooNE and MiniBooNE results is likely due to several factors: (i) the presence in the MiniBooNE target of the proton, which is free of nuclear effects; (ii) the differences in the two fluxes, with the MiniBooNE one having a mean neutrino energy slightly larger; (iii) a larger role of pion FSI in ^{40}Ar than in ^{12}C; and maybe (iv) contamination in the case of MiniBooNE of the two-pion production channel, which could simulate one-pion emissions if one of the pions is absorbed on its way out. Concerning our evaluations, we remark small differences between the ^{40}Ar and ^{12}C results, with ^{12}C being slightly larger. For the coherent pion production, this is expected since this channel decreases with the mass number.

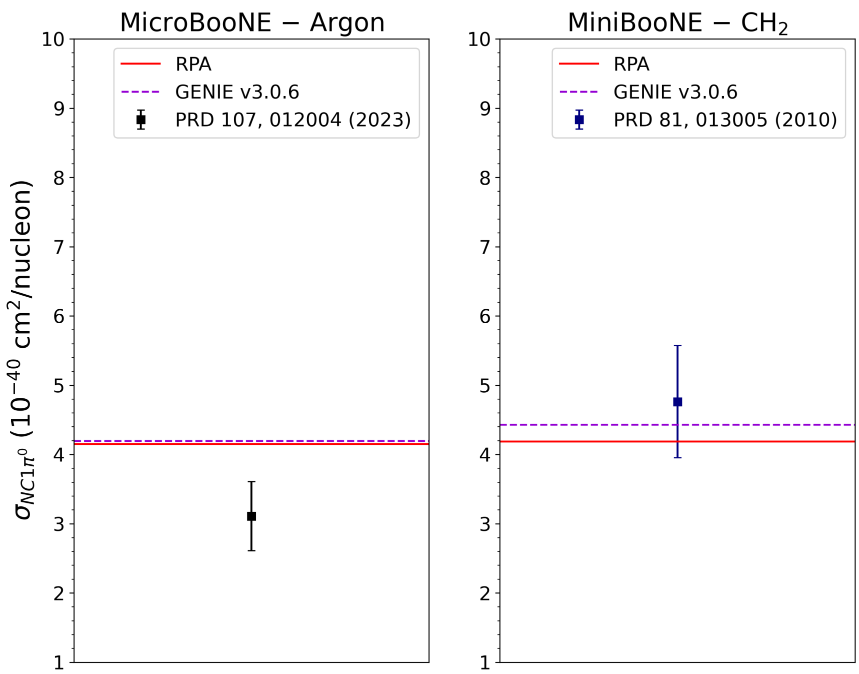

Figure 2. Comparison of the MicroBooNE [1] NC1π^0 cross section on argon (left) as well as that from MiniBooNE [15] on mineral oil CH_2 (right), to our RPA predictions and to the GENIE v3.0.6 [16] results.

Table 1. Comparison between our RPA predictions and the measurements performed by MicroBooNE [1] on ^{40}Ar and MiniBooNE on CH_2 [15] for the NC1π^0 flux-integrated total cross section. In our predictions, we use the four ν_μ, ν_e, $\bar{\nu}_\mu$, $\bar{\nu}_e$ MicroBooNE fluxes, while we consider only the ν_μ MiniBooNE flux.

σ NC1π^0	σ [10^{-40}cm^2/nucleon]
RPA NC1π^0 incoherent on ^{40}Ar	3.74
RPA NC1π^0 coherent on ^{40}Ar	0.22
RPA NC1π^0 on ^{40}Ar	**3.96**
MicroBooNE NC1π^0 on ^{40}Ar [1]	$3.11 \pm 0.19_{stat} \pm 0.46_{sys}$
RPA NC1π^0 incoherent on ^{12}C	3.90
RPA NC1π^0 coherent on ^{12}C	0.24
NC1π^0 on proton	4.44
RPA NC1π^0 on CH_2	**4.19**
MiniBooNE NC1π^0 on CH_2 [15]	$4.76 \pm 0.05_{stat} \pm 0.76_{sys}$

The MicroBooNE collaboration [1] also measured separately the NC1π^0 exclusive cross sections with one proton (1p) or zero protons (0p) in the final state. The unequal number of neutrons and protons in argon should be reflected in these data. In the two measured channels, neutral pion production with 1 or 0 protons is depicted in the two graphs of Figure 3. Z^0 excites Δ^+ in the first case and Δ^0 in the second case. Neutron emission is favoured over proton emissions by a larger number of neutrons in ^{40}Ar. Under the condition of an identical branching ratio for $\Delta^+ \to \pi_0 p$ and $\Delta_0 \to \pi_0 n$, which is satisfied, see Equation (3), the ratio between the two cross sections is:

$$\frac{18}{22} = 0.818,$$

the ratio of protons to neutrons in argon. This number can be confronted to the one obtained by the ratio of the experimental cross sections:

$$\frac{\sigma_{NC1\pi^0+1p}}{\sigma_{NC1\pi^0+0p}} = 0.711 \pm 0.330.$$

The agreement between these two numbers can be considered as good in view of the experimental uncertainty, obtained by summing in quadrature the total experimental errors.

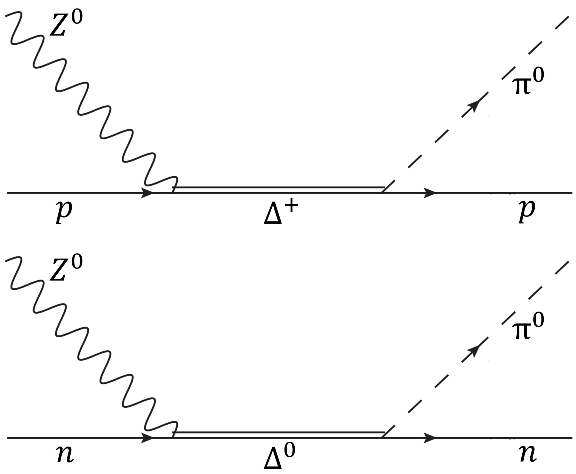

Figure 3. Diagrammatic representation of the Δ-mediated NC 1 π^0 production.

3. Summary and Conclusions

In summary, we have interpreted the recent MicroBooNE data [1] on single π^0 production by neutral currents with our hypothesis that pion production at moderate neutrino energies occurs via Delta excitation. With this assumption, we have described successfully the data for the flux-integrated total cross section and also for the ratio between the two exclusive measurements with one proton and zero protons in the final state. In the near future, we plan to also investigate the charged-current neutral pion production and compare our predictions with the corresponding MicroBooNE cross section measurements that have recently appeared [18].

Author Contributions: Conceptualization, G.C., M.E. and M.M.; methodology, G.C., M.E. and M.M.; software, M.M.; validation, G.C., M.E. and M.M.; formal analysis, M.E. and M.M.; writing—original draft preparation, M.E. and M.M.; writing—review and editing, G.C., M.E. and M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: We acknowledge T. Ericson for interesting discussions.

Conflicts of Interest: The authors declare no conflicts of interest.

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