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COHERENT NEUTRINO SCATTERING*

M. Valverde

Research Center for Nuclear Physics (RCNP), Osaka University
Ibaraki 567-0047, Japan

J.E. Amaro

Dpto. Física Atómica, Molecular y Nuclear, University de Granada
18071 Granada, Spain

E. Hernandez

Grupo de Física Nuclear, Dpto. de Física Fundamental e IUFFyM
Facultad de Ciencias, 37008 Salamanca, Spain

J. Nieves

Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Univ. de Valencia
Institutos de Investigación de Paterna, Aptd. 22085, 46071 Valencia, Spain

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We present a microscopic model for coherent pion production off nuclei induced by neutrinos. This model is built upon a model for single nucleon processes that goes beyond the usual Δ dominance by including non resonant background contributions. We include nuclear medium effects: medium corrections to Δ properties and outgoing pion absorption via an optical potential. This results in major modifications to cross-sections for low energy experiments when compared with phenomenological models like Rein–Sehgal's.

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A proper understanding of neutrino-induced pion production off nuclei is very important in the analysis of neutrino oscillation experiments. For instance, π^0 production by neutral currents (NC) is the most important ν_μ-induced background to $\nu_\mu \to \nu_e$ oscillation experiments, [1]. Similarly,

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π^+ production by charged currents (CC) is an important source of background in $\nu_\mu \to \nu_x$ disappearance searches [2]. We will follow [3] to describe the coherent CC pion production reaction induced by neutrinos

$$\nu_l(k) + \left. A_Z\right|_{\rm gs}(p_A) \to l^-(k') + \left. A_Z\right|_{\rm gs}(p'_A) + \pi^+(k_\pi)\,, \qquad (1)$$

where the nucleus is left in its ground state, in contrast to incoherent reactions where the nucleus is broken or left on an excited state.

We build upon a microscopic model for the single nucleon process ($\nu N \to l^- N\pi^+$). We sum coherently the contribution of all nucleons on the initial nuclei, which is modeled after a Fermi gas in Local Density Approximation. Coherent π production is most sensitive to the Fourier transform of the nuclear density for momentum $\vec{q}-\vec{k}_\pi$, which gets its maximum value when $\vec{q}$ and $\vec{k}_\pi$ are parallel. For this particular kinematics the vector contribution to the single nucleon ($W+N \to N\pi$) currents, which is purely transverse $\vec{k}_\pi \times \vec{q}$, vanishes unlike the axial contribution. This dominance of the axial contributions is exploited through the PCAC hypothesis by the Rein–Sehgal (RS) model [4, 5], to relate the neutrino coherent pion production cross-section with the pion–nucleus elastic differential one.

For the elementary process we use the model derived in Ref. [6], see Fig. 1. In addition to the $\Delta(1232)$ pole (ΔP) (first row) mechanism the model includes background terms required by chiral symmetry: nucleon (second row) pole terms (NP, CNP) contact (CT) and pion pole (PP) contribution (third row) and pion-in-flight (PF) term. Background terms turn out to

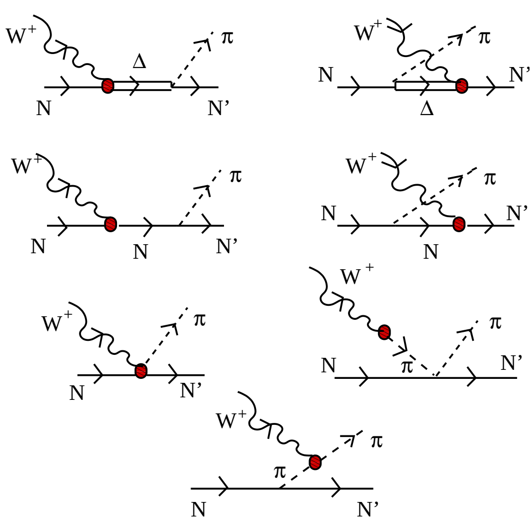

Fig. 1. Model for the $W^+N \to N'\pi$ reaction. The circle in the diagrams stands for the weak vertex.

be very important and because of them, the flux-averaged $\nu_\mu p \to \mu^- p\pi^+$ ANL cross-section [10, 11] is described with an axial form factor where the dominant C_5^A nucleon-to-Δ axial form factor was fit to data resulting in $C_5^A(0) = 0.867$ and $M_{A\Delta} = 0.985$ GeV. This value for $C_5^A(0)$ is significantly smaller than the value of about 1.2 deduced from the Golberger–Treiman relation (GTR) used in PCAC-based approaches like RS.

When applied to a coherent process in finite nuclei we find that the NP and CNP nucleon pole term contributions partially cancel each other, that the PF term does not contribute to the coherent cross-section and the CT and PP terms vanish for isospin symmetric nuclei. As seen in Fig. 2 the effect of the background terms, both in the plane wave impulse approximation (PWIA) and in the full model calculation, is very small. Thus, we predict cross-sections around a factor of $(1.2/0.9)^2 \sim 2$ smaller than approaches assuming GTR. In the following we will always use the full model of Ref. [6] with $C_5^A(0) = 0.867$ and $M_{A\Delta} = 0.985$ GeV.

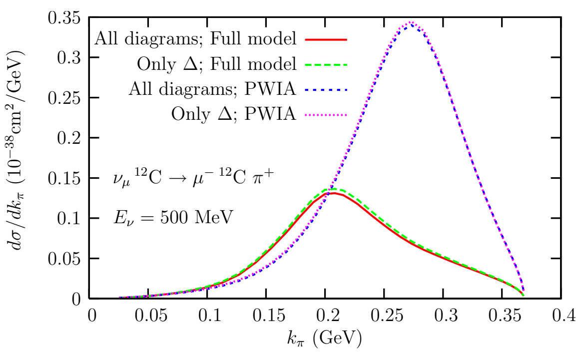

Fig. 2. Pion momentum differential LAB cross-section, with and without background terms.

Nuclear medium corrections to the dominant Δ diagram are considered by including the self-energy of the Δ in the medium, Ref. [7]. Another major nuclear medium effect is pion distortion, which takes this into account by replacing the plane wave with a pion wave function incoming solution of a Klein–Gordon equation with a microscopic optical potential, Ref. [8]. In the left panel of Fig. 3 we show the pion momentum distribution (LAB) for CC coherent pion production, in the peak energy region of the T2K experiment. Including Δ in-medium self-energy (long-dashed line) reduces the PWIA results (short-dashed line). Further inclusion of pion distortion (full model, solid line) reduces the cross-section, and the peak is shifted towards lower energies. The total cross-section reduction is around 60%. Medium and pion distortion effects in coherent pion production were already evaluated in Refs [9]. However, the authors of these references neglected the nucleon

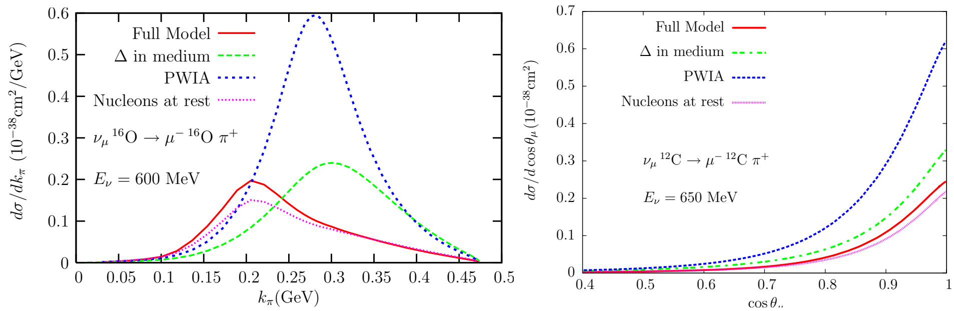

Fig. 3. Right panel: Pion momentum differential cross-section in the LAB frame. Left panel: Pion angular differential cross-section.

momenta in the Dirac spinors. The effect of this approximation (nucleons at rest, dotted line) results in a $\sim 15\%$ decrease of the total cross-section. In the right panel of Fig. 3 we show the pion angular LAB distribution with respect to the incoming neutrino direction. The reaction is very forward peaked, as expected due to the nucleus form factor. The angular distribution profile keeps its forward peaked behavior after introduction of nuclear medium effects.

We examine in Fig. 4 the NC differential cross-section with respect to the variable $E_\pi(1-\cos\theta_\pi)$, proposed by MiniBooNE. Our prediction is appreciably narrower than that displayed in Fig. 3(b) of Ref. [1]. The MiniBooNE analysis relies on the RS model, so we try to understand the differences between this and our model. RS's expression for the coherent π^0 production cross-section was deduced in the parallel configuration, for which the k_μ and k'_μ four momenta are proportional ($q^2 = 0$) and $\vec{k}_\pi \approx \vec{q}$ is assumed everywhere except in the nuclear form factor. Thus, the RS differential cross-section depends on $\cos\theta_\pi$ or t only through the nuclear form factor and any further $\cos\theta_\pi$ or t behaviour induced by the dependence of the amplitudes on k_π is totally neglected. This is a good approximation at neutrino energies above 2 GeV. However, at the energies relevant in the MiniBooNE and T2K experiments non parallel configurations become important, and the RS model less reliable. We have re-derived RS's expression within our model by considering only the dominant axial part of the ΔP process ($\sim C_5^A$), neglecting nuclear medium corrections and replacing k_π by q in the pion emission vertex. In the right panel of Fig. 4 we see that the new $E_\pi(1-\cos\theta_\pi)$ distribution is significantly wider than that obtained without implementing this replacement and that it reasonably describes the MiniBooNE published distribution (solid histogram). The agreement is much better when compared with some preliminary MiniBooNE results (dashed histogram) obtained with a different treatment of the outgoing pion distortion. This calculation shows the uncertainties associated to the $t = 0$ approximation at low energies.

Pion distortion induces some additional discrepancies. MiniBooNE implement this effects through a Monte Carlo cascade model for the π propagation in medium. However, coherent cross-sections cannot be calculated from a Monte Carlo cascade algorithm, because the coherent production is a one step process and by using a Monte Carlo algorithm we break the coherence of the process. Nevertheless, one could still reasonably estimate the total coherent cross-section from the NUANCE FSI cascade if it is used to eliminate from the flux not only those pions which get absorbed or suffer inelastic processes but also those that undergo QE steps. To our knowledge, these latter events are accounted for in the MiniBooNE analysis, despite not being coherent. In our calculation the imaginary part of the pion–nucleus potential removes from the flux of the outgoing pions those that are absorbed or undergo QE interactions. We try to estimate this effect by switching off the QE contribution to the pion–nucleus optical potential induced by elastic pion–nucleon collisions, and using an optical potential with an imaginary part due to absorption and inelastic channels alone. For the MiniBooNE flux averaged cross-section we find a 20% enhancement (see NC* entry in Table I) in good agreement with the effects observed by turning off the NUANCE FSI. We conclude that the RS model is not as reliable for MiniBooNE and T2K experiments as for the ν energies above 2 GeV. Our model provides an $E_\pi(1-\cos\theta_\pi)$ distribution much more peaked, and thus it might improve the description of the first bin value in Fig. 3(b) of Ref. [1].

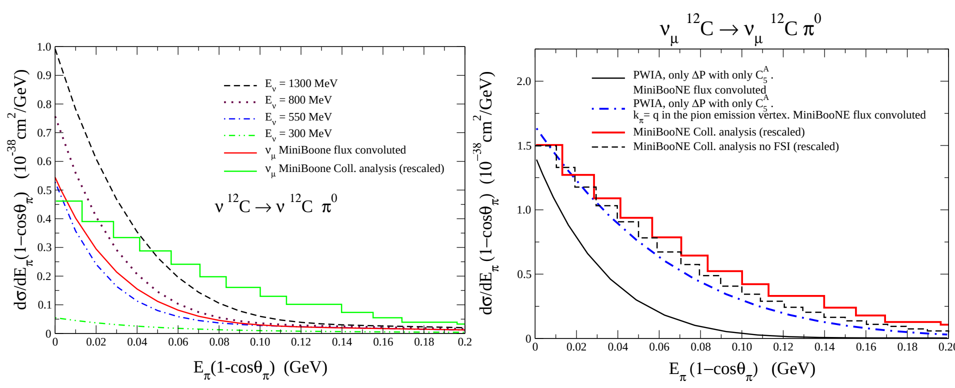

Fig. 4. Laboratory $E_\pi(1-\cos\theta_\pi)$, at MiniBooNE energies. In the left panel we use our full model including full nuclear corrections. In the right panel, we show results from the C_5^A axial contribution of the ΔP mechanism, neglecting pion distortion and Δ in medium effects. We display the MiniBooNE published histogram (solid), conveniently scaled down, from Ref. [1] and MiniBooNE results (dashed histogram) obtained by turning off the NUANCE FSI of the outgoing pion [G. Zeller, private communication].

Moreover, the drastic change in the $E_\pi(1-\cos\theta_\pi)$ distribution shape might produce some mismatch between the absolute normalization of the background, coherent and incoherent yields in the MiniBooNE analysis.

In Table I we show our predictions for the MiniBooNE, K2K and T2K [14] flux averaged cross-sections. Since our model neglects all resonances above the Δ, our predictions become less reliable when the energy increases, so we set up a maximum neutrino energy in the flux convolution $E_{\rm max}$, neglecting the long tail of the ν flux. Up to these energies, one can assume Δ dominance and still cover about 90% of the total flux (65% for T2K antineutrino flux). We expect corrections (higher cross-sections) of around 20–30% to our results for MiniBooNE and T2K (larger for K2K). Our prediction lies well below the K2K upper bound, while being notably smaller than that given in [12] for NC MiniBooNE. However, notice the previous discussion on RS model, which is being used in the MiniBooNE analysis. The K2K cross-section and the value quoted in Ref. [12] seems somehow incompatible with the approximate relation $\sigma_{\rm CC} \approx 2\sigma_{\rm NC}$, expected from Δ-dominance and neglecting finite muon mass effects.

TABLE I

Coherent pion production total cross-sections.

Reaction	Exp.	$\bar\sigma[10^{-40}{\rm cm}^2]$	$\sigma_{\rm exp}[10^{-40}{\rm cm}^2]$	$E_{\rm max}$ [MeV]
CC $\nu_\mu+^{12}$C	K2K	4.68	<7.7 [13]	1.80
CC $\nu_\mu+^{12}$C	MiniBooNE	2.99	—	1.45
CC $\nu_\mu+^{12}$C	T2K	2.57	—	1.45
CC $\nu_\mu+^{16}$O	T2K	3.03	—	1.45
NC $\nu_\mu+^{12}$C	MiniBooNE	1.97	$7.7\pm1.6\pm3.6$ [12]	1.34
NC* $\nu_\mu+^{12}$C	MiniBooNE	2.38	$7.7\pm1.6\pm3.6$ [12]	1.34
NC $\nu_\mu+^{12}$C	T2K	1.82	—	1.34
NC $\nu_\mu+^{16}$O	T2K	2.27	—	1.35
CC $\bar\nu_\mu+^{12}$C	T2K	2.12	—	1.45
NC $\bar\nu_\mu+^{12}$C	T2K	1.50	—	1.34

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