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A relativistic model for neutrino pion production from nuclei in the resonance region

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Abstract.
We present a relativistic model for electroweak pion production from nuclei, focusing on the Δ and the second resonance region. Bound states are derived in the Hartree approximation to the $\sigma-\omega$ Walecka model. Final-state interactions of the outgoing pion and nucleon are described in a factorized way by means of a relativistic extension of the Glauber model. Our formalism allows a detailed study of neutrino pion production through Q^2, W, energy, angle and out-of-plane distributions.

Keywords: neutrino interactions, pion production, resonance region, Glauber approximation
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Lately, new cross-section measurements presented by the MiniBooNE and K2K collaborations have put the spotlights on few-GeV neutrino-scattering physics. As nuclei serve as neutrino detectors in these experiments, there is a great deal of interest in modeling neutrino-nucleus interactions in the region $W < 2$ GeV, where the vast part of the strength is due to quasi-elastic events and resonant one-pion production. The need for a realistic description of nuclear effects becomes even more evident in the light of future neutrino-scattering experiments like Minerνa, who aim at a precise study of various exclusive channels with the use of high-intensity beams and improved particle identification.
In earlier work, neutrino-induced one-nucleon knockout calculations have been performed within the relativistic multiple-scattering Glauber approximation [1]. Here, we proceed along the same lines to develop a framework for resonant one-pion production calculations. The presented formalism focuses on an intermediate Δ state, but can be straightforwardly extended to the second-resonance region.

For a nucleus with mass number A, the process under consideration can be schematically represented as

$$\nu + A \xrightarrow{\Delta} l + N + \pi + (A-1), \tag{1}$$

with l, N and π representing the outgoing charged lepton, nucleon and pion respectively. In the laboratory system, the eightfold cross section for the process (1) is given by

$$\frac{d^8\sigma}{dE_l d\Omega_l dE_\pi d\Omega_\pi d\Omega_N} = \frac{m_l|\vec{k}_l|}{(2\pi)^3}\frac{M_N M_{A-1}|\vec{k}_\pi||\vec{k}_N|}{2(2\pi)^5|E_{A-1}+E_N+E_N\vec{k}_N\cdot(\vec{k}_\pi-\vec{q})/|\vec{k}_N|^2|}\sum_{if}|M_{fi}|^2, \tag{2}$$

using self-explanatory notations for the outgoing particles' kinematics.
All information about the reaction dynamics is contained in the matrix element

$$M_{fi} = i\frac{G_F \cos\theta_c}{\sqrt{2}} \overline{u}(k_N, s_N)\Gamma^{\mu}_{\Delta\pi N}(k_\pi, k_\Delta)S_{\Delta,\mu\nu}(k_\Delta)\Gamma^{\nu\rho}_{WN\Delta}(k_\Delta, q)S_{W,\rho\sigma}(q)J^{\sigma}_{l}u_{\alpha,m}(k_i), \tag{3}$$

where G_F and θ_c stand for the Fermi constant and the Cabibbo mixing angle. In (3), we adopted the impulse approximation. The hit nucleon is represented by the bound-state spinor $u_{\alpha,m}(k_i)$, calculated as the Fourier transform of the bound-state wave functions

$$\Psi_{\alpha,m}(\vec{r}) = \begin{pmatrix} i\frac{G(r)}{r}\mathscr{Y}_{+\kappa,m}(\hat{\vec{r}}) \\ -\frac{F(r)}{r}\mathscr{Y}_{-\kappa,m}(\hat{\vec{r}}) \end{pmatrix}. \tag{4}$$

The radial wave functions in (4) are determined in the Hartree approximation to the $\sigma - \omega$ Walecka model [2]. Further, J_l represents the weak lepton current and S_W is the weak boson propagator. To describe the Δ-production vertex $\Gamma_{WN\Delta}$, we turn to the phenomenological form-factor parameterization discussed in [3]. The adopted form factors are constrained by theoretical principles like CVC and PCAC and, in the case of the vector form factors, by available electron-scattering data. For the Δ propagator we take the Rarita-Schwinger propagator for a spin-3/2 particle. In this regard, medium modifications of the resonance are accounted for by implementing a shift to the mass and width of the Δ. We hereby use a density-dependent parameterization suggested in [4], and based on a calculation of the Δ self energy in the medium. Finally, the decay of the Δ particle is described by the interaction $\Gamma_{\Delta\pi N}$, and $\overline{u}(k_N, s_N)$ represents the outgoing nucleon's spinor.
Next to binding effects and medium-modified Δ properties, the final-state interactions (FSI) of the escaping nucleon and pion can have a considerable effect on the calculated cross-section strength. To compute the influence of FSI, we adopt a relativistic multiple-scattering Glauber approximation (RMSGA) [5]. Within this RMSGA model, one computes the attenuation of *fast* nucleons and pions due to elastic and mildly inelastic collisions with the remaining *spectator* nucleons when they travel through the nucleus. The Glauber approach allows to calculate the probability that a high-energy nucleon/pion will escape from a finite nucleus [6, 7], a quantity often referred to as the nuclear transparency. In Ref. [1], it was shown that plane-wave $(\nu, \nu' N)$ cross sections corrected with this nuclear transparency factor provide an excellent alternative for full, unfactorized distorted-wave calculations, provided that inclusive cross sections are considered.

In short, we have presented a fully relativistic formalism for neutrino one-pion production on nuclei in the resonance region. This framework opens up a wide range of possibilities: we can do calculations for different nuclei and resonances. Moreover, predictions can be made for various observables, including not only Q^2 and W distributions, but also energy and angular distributions for the outgoing lepton or hadrons (Fig. 1). As an accurate description of nuclear effects will be of notable interest to future neutrino-scattering experiments, we account for nuclear binding effects, medium-modified resonance properties and FSI effects [8].

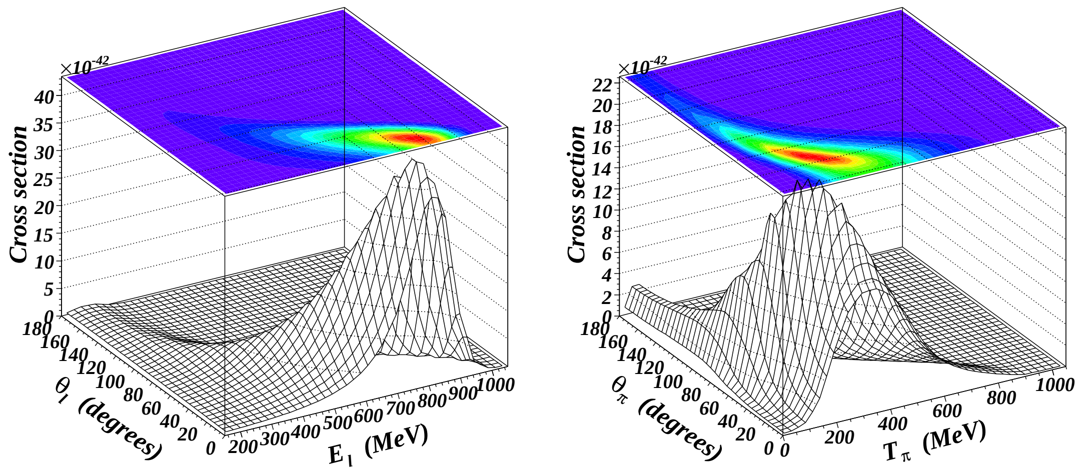

FIGURE 1. Two-fold distributions for the process $\nu_\mu + p \rightarrow \mu + \Delta^{++}$ on a carbon nucleus for $E_\nu =$ 1200 MeV.

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