PROCEEDINGS OF SCIENCE

Neutrino-induced one-pion production from nuclei

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We outline a fully relativistic formalism for describing neutrino-induced Δ-mediated single-pion production in nuclei. To describe the nucleus, we turn to a relativistic plane-wave impulse approximation (RPWIA) using realistic bound-state wave functions derived in the Hartree approximation to the σ-ω Walecka model. Medium modifications of the Δ mass and width are accounted for within a scheme that gives good results in photo-induced two-nucleon knockout reactions. As an application, we present Δ-mediated one-pion production calculations for the typical MiniBooNE kinematics. It is found that medium modifications roughly halve the RPWIA cross sections. The model presented in this work can be naturally extended to include the effect of final-state interactions in a relativistic and quantum-mechanical way.

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1. Introduction

The MiniBooNE and K2K collaborations recently collected a wealth of neutrino data in the 1-GeV energy range. In this energy regime, a great deal of events can be attributed to Δ-mediated one-pion production. Hence, a thorough understanding of these cross sections is essential to reduce the systematic uncertainties related to the inaccurate description of this process. In turn, the high-statistics data from planned neutrino experiments like MINERνA and SciBooNE will offer the opportunity to address a variety of topics related to hadronic and nuclear weak physics.
In section 2, we cover the main ingredients of our relativistic framework, together with the nuclear-physics input. Section 3 is dedicated to a discussion of one-pion production calculations at MiniBooNE kinematics.

2. Delta-mediated one-pion production in nuclei

A schematic representation of the reaction under study is given by

$$\nu_\mu + A \xrightarrow{\Delta} \mu^- + (A-1) + N + \pi, \tag{2.1}$$

where A denotes the mass number of the target nucleus. The lab-frame cross section corresponding to the process of Eq. (2.1) becomes [1]

$$\frac{d^8\sigma}{dE_l d\Omega_l dE_\pi d\Omega_\pi d\Omega_N} = \frac{m_\nu m_l |\vec{k}_l| m_N m_{A-1} |\vec{k}_\pi||\vec{k}_N|}{2(2\pi)^8 E_\nu |E_{A-1} + E_N + E_N \vec{k}_N \cdot (\vec{k}_\pi - \vec{q})/|\vec{k}_N|^2|} \overline{\sum}_{fi} |M_{fi}^{(bound)}|^2. \tag{2.2}$$

2.1 Relativistic bound-state wave functions

Adopting the impulse approximation (IA) and assuming an independent-particle model (IPM) for the initial and final nuclear wave functions, the hadronic current matrix elements can be written in the form

$$\langle J_{had}^{\rho(bound)} \rangle = \bar{u}(k_N, s_N) \Gamma^{\mu}_{\Delta\pi N} S_{\Delta,\mu\nu} \Gamma^{\nu\rho}_{WN\Delta} \mathscr{U}_\alpha(\vec{p}_m), \tag{2.3}$$

where the $\mathscr{U}_\alpha$ are the bound-state wave functions in momentum space, which are calculated in the Hartree approximation to the σ-ω Walecka model [2]. In Eq. (2.3), $\Gamma^{\nu\rho}_{WN\Delta}$ is the form-factor parameterized Δ-production vertex, $S_{\Delta,\mu\nu}$ the Rarita-Schwinger propagator and $\Gamma^{\mu}_{\Delta\pi N}$ the decay vertex [1]. In the case the outgoing nucleon remains unaffected by the nuclear medium, it is represented by the free Dirac spinor $u(k_N, s_N)$.

2.2 Medium modifications of Δ properties

In a nuclear environment, the Δ mass and width are modified with respect to their free values. A convenient parameterization is given in Ref. [3], in terms of the nuclear density ρ. Adopting an average nuclear density $\rho = 0.75\rho_0$, we calculate the following shifts

$$\begin{aligned} M_\Delta &\longrightarrow M_\Delta + 30 \text{ MeV}, \\ \Gamma &\longrightarrow \Gamma + 40 \text{ MeV}. \end{aligned} \tag{2.4}$$

In Ref. [4], a similar recipe was used to accommodate medium modifications in the calculation of $^{12}\mathrm{C}(\gamma, pn)$ and $^{12}\mathrm{C}(\gamma, pp)$ cross sections. These computations proved to compare favorably with the data in an energy regime where the reaction is dominated by Δ creation.

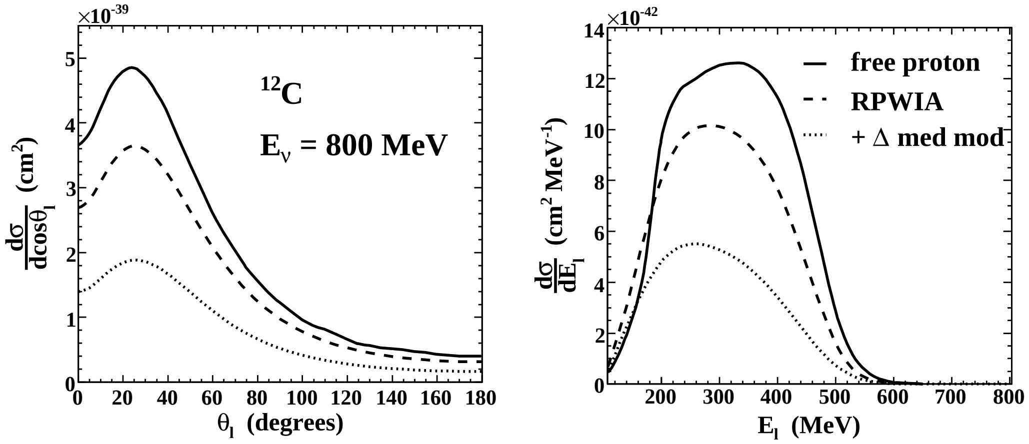

Figure 1: Cross sections per nucleon for $\nu_\mu + p \xrightarrow{\Delta^{++}} \mu^- + p + \pi^+$. The left (right) panel shows the cross section as a function of the outgoing-muon scattering angle (energy). Each of the panels contrasts the free-proton cross section (full line) with the RPWIA result, shown with (dotted) and without (dashed) Δ medium modifications.

3. Results

In Fig. 1, we show $(\nu_\mu, \mu^- \pi^+ p)$ cross sections for an incoming neutrino energy of 800 MeV and a carbon target nucleus. Relative to the free cross section, the RPWIA angular distribution for a carbon target is reduced by about 20%. The RPWIA energy distribution fades out sooner than the elementary cross section, because a certain amount of energy is needed to knock the carbon protons out of their shell. Further, Fig. 1 shows that the inclusion of Δ medium modifications results in a 50% reduction of the RPWIA cross sections. It is important to note that roughly 20% of the reduced strength will reappear in the pion-less Δ-decay channel, which is not taken into account here [1]. Future work will focus on the inclusion of final-state interactions for the ejected pions and nucleons. To this end, we closely follow the lines of Ref. [5], where use is made of a relativistic Glauber model for fast ejectiles and an optical-potential approach for lower ejectile energies.

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