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MODELING NEUTRINO–NUCLEUS INTERACTIONS IN THE FEW-GeV REGIME*

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We present calculations for quasi-elastic inclusive neutrino-induced nucleon knockout reactions on atomic nuclei. Final-state interactions (FSI) are introduced using a relativistic multiple-scattering Glauber approximation (RMSGA). For interactions at low energies, long-range correlations are implemented by means of a continuum random phase approximation (CRPA) approach.

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1. Introduction

The recent experimental confirmation of neutrino oscillations sparked off an enormous experimental and theoretical interest in the oscillation properties of these particles. Several collaborations are working on the extension of the present knowledge about neutrino masses and mixing angles, so as to complete the picture about the non-standard neutrino behavior. For an accurate interpretation of the experimental data, a thorough understanding of the interactions involved in oscillation experiments is indispensable. Cross-sections for neutrino–nucleus interactions play an important role. Whereas the experimental observable is often an inclusive cross-section, a detailed study of exclusive cross-sections is indispensable for a thorough understanding of these processes.

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2. Quasi-elastic neutrino scattering

The one-fold differential cross-section is given by

$$\begin{aligned}\frac{d\sigma}{dT_N} &= \frac{M_N M_{A-1}}{(2\pi)^3 M_A} 4\pi^2 \int \sin\theta_l d\theta_l \int \sin\theta_N d\theta_N k_N f_{\mathrm{rec}}^{-1} \sigma_{\mathrm{M}} \\ &\quad \times \left[v_{\mathrm{L}} R_{\mathrm{L}} + v_{\mathrm{T}} R_{\mathrm{T}} + h v_{\mathrm{T}'} R_{\mathrm{T}'} \right] , \end{aligned} \tag{1}$$

with M_N, T_N and $\vec{k}_N$ the mass, kinetic energy and momentum of the ejectile, M_A and M_{A-1} the mass of the target and residual nuclei. The direction of the outgoing lepton and nucleon is determined by $\Omega_l(\theta_l, \phi_l)$ and $\Omega_N(\theta_N, \phi_N)$. The recoil factor is denoted by f_{rec}. The quantity σ_{M} is the weak variant of the Mott cross-section

$$\sigma_{\mathrm{M}}^{Z} = \left(\frac{G_{\mathrm{F}} \cos(\theta_l/2) \varepsilon' M_Z^2}{\sqrt{2}\pi (Q^2 + M_Z^2)} \right)^2 , \tag{2}$$

for neutral current processes, and

$$\sigma_{\mathrm{M}}^{W^\pm} = \sqrt{1 - \frac{M_l'^2}{\varepsilon'^2}} \left(\frac{G_{\mathrm{F}} \cos\theta_c \cos(\theta_l/2) \varepsilon' M_W^2}{2\pi (Q^2 + M_W^2)} \right)^2 , \tag{3}$$

for charged current reactions. In these equations, G_{F} is the weak interaction Fermi coupling constant, θ_{C} the Cabibbo angle, M_Z and M_W the weak boson masses, M_l' the mass of the outgoing lepton, ε' the energy of the outgoing lepton, and $Q^2 = -q_\mu q^\mu$ the transferred four momentum. In Eq. (1), v_{L}, v_{T} and $v_{\mathrm{T}'}$ are the longitudinal, transverse and interference kinematic factors and R_{L}, R_{T} and $R_{\mathrm{T}'}$ the accompanying structure functions, reflecting the influence of nuclear dynamics on the scattering process [2]. The helicity of the incoming neutrino is denoted by h. The basic quantities in the computation of these response functions are the transition matrix elements $\langle J^\mu \rangle$. Within an independent-nucleon model and adopting the impulse approximation, the matrix elements of the weak current operator $\widehat{J}^\mu$ can be expressed as

$$\langle J^\mu \rangle = \int d\vec{r}\, \overline{\phi}_F(\vec{r}) \widehat{J}^\mu(\vec{r}) e^{i\vec{q}\cdot\vec{r}} \phi_B(\vec{r}) \,, \tag{4}$$

with $\phi_B(\vec{r})$ and $\phi_F(\vec{r})$ the relativistic bound-state and scattering wave-functions, respectively. In our numerical calculations, bound-state wave-functions are obtained within the Hartree approximation to the σ–ω model, adopting the W1 parameterization for the different field strengths.

3. Final state interactions

We present cross-section calculations based on a relativistic mean-field model, and introduce final-state interactions adopting a relativistic multiple-scattering Glauber approximation (RMSGA) [1, 2]. As a semi-classical approach, this technique exploits the advantages of the kinematics conditions reigning at sufficiently high energies, where high momentum transfers strongly favor forward elastic scattering of the outgoing nucleon. The Glauber technique assumes linear trajectories for the ejectile and frozen spectator nucleons in the residual system. The influence of the nuclear medium on the outgoing nucleon's wave-function is condensed in the eikonal phase $\mathcal{G}[\vec{b}(x,y),z]$, that summarizes the effects of the scattering reactions the ejectile undergoes. This results in a scattering wave-function that can be written as

$$\phi_F(\vec{r}) = \mathcal{G}\left[\vec{b}(x,y),z\right]\ \phi_{k_N,s_N}(\vec{r}), \tag{5}$$

with $\phi_{k_N,s_N}(\vec{r})$ a relativistic plane wave. In the limit of vanishing final-state interactions ($\mathcal{G}=1$) , the formalism becomes equivalent to the relativistic plane wave impulse approximation (RPWIA) [2]. Figure 1 shows the influ-

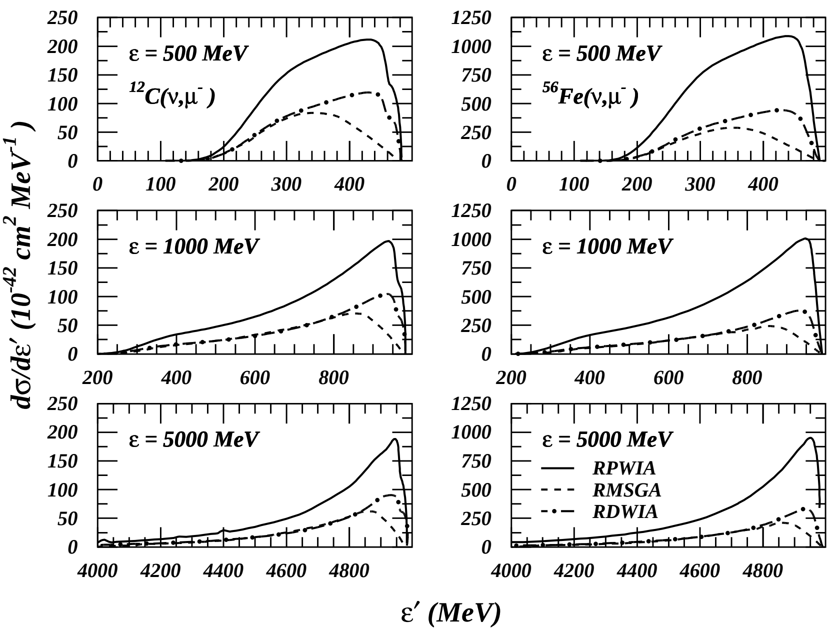

Fig. 1. Cross-sections for the charged-current reactions $^{12}\mathrm{C}(\nu_\mu,\mu^-)$ and $^{56}\mathrm{Fe}(\nu_\mu,\mu^-)$ as a function of the energy of the outgoing muon ε'. The different curves compare the RMSGA results (dashed) with the RDWIA (dash-dotted) and the RPWIA limit (full line).

ence of final state interactions on cross-sections for charged-current processes on ^{12}C and ^{56}Fe, and compares Glauber and RDWIA calculations. In the region where both approaches are valid, their results are in excellent agreement.

4. Strangeness

The strangeness content of the nucleon influences neutrino–nucleus cross-sections and has an important impact on several cross-section ratios. We studied (anti)neutrino cross-section ratios and compared the influence of axial as well as vector strangeness in terms of ejectile energies and Q^2 values.

We compared the impact of the weak strangeness form factors on the ratio of proton-to-neutron knockout, the ratio of neutral-to-charged current cross-sections, on the Paschos–Wolfenstein relation

$$R^N_{\mathrm{PW}} = \frac{\frac{d\sigma}{dT_N}(\nu N \to \nu N) - \frac{d\sigma}{dT_N}(\overline{\nu} N \to \overline{\nu} N)}{\frac{d\sigma}{dT_N}(\nu n \to \mu^- p) - \frac{d\sigma}{dT_N}(\overline{\nu} p \to \mu^+ n)}\,, \tag{6}$$

for protons ($N = p$) and neutrons ($N = n$), and on the longitudinal helicity asymmetry for neutrinos and antineutrinos

$$A_l^{\overset{(-)}{\nu}} = \frac{\frac{d\sigma}{dT_p}\left(\overset{(-)}{\nu}\, p \to \overset{(-)}{\nu}\, p,\, h_p = +1\right) - \frac{d\sigma}{dT_p}\left(\overset{(-)}{\nu}\, p \to \overset{(-)}{\nu}\, p,\, h_p = -1\right)}{\frac{d\sigma}{dT_p}\left(\overset{(-)}{\nu}\, p \to \overset{(-)}{\nu}\, p,\, h_p = +1\right) + \frac{d\sigma}{dT_p}\left(\overset{(-)}{\nu}\, p \to \overset{(-)}{\nu}\, p,\, h_p = -1\right)}\,. \tag{7}$$

Figure 2 summarizes the main results. The longitudinal helicity asymmetry for antineutrinos is most sensitive to strangeness effects. In general, antineutrino-induced processes exhibit a more outspoken strangeness sensitivity than their neutrino counterparts. The overall sensitivity of $R_{\mathrm{NC/CC}}$ ratios to strangeness effects is considerably smaller than that of $R_{p/n}$, but at small Q^2, the strangeness contributions to $R_{\mathrm{NC/CC}}$ are more strongly dominated by the axial channels [3].

Although neutrino scattering is usually regarded as an excellent lever for extracting information about the axial strangeness, strange vector form factors have a remarkably strong influence on these ratios. Whereas in parity-violating electron scattering (PVES) the tininess of the axial strangeness effects impedes the determination of g_A^s, in neutrino scattering a thorough understanding of vector strangeness effects is a prerequisite for extracting information on the axial strangeness. Hence a combined analysis of PVES and neutrino-induced processes would offer the best prospects for a thorough understanding of the influence of the nucleon's strange quark sea on electroweak processes.

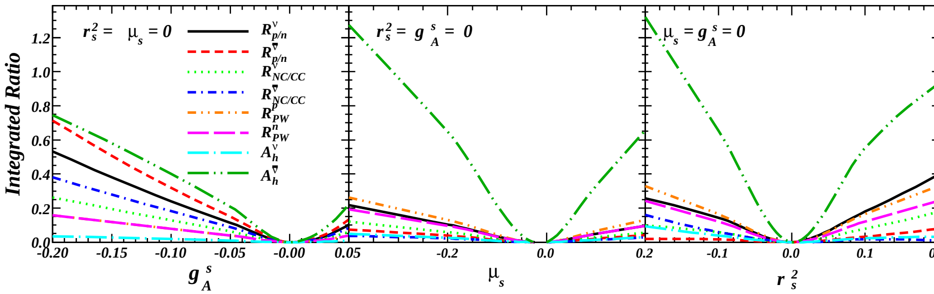

Fig. 2. Comparison between the strangeness influence on various ratios of total cross-sections in terms of the relative sensitivity $\left|\frac{R(s=0)-R(s)}{R(s=0)}\right|$, as a function of the strangeness form factors g_A^s, μ_s and r_s^2 for 1 GeV neutrino scattering off ^{12}C.

5. Long-range CRPA correlations

In a Random Phase Approximation (RPA) approach, long-range correlations between the nucleons in the nucleus are introduced. These become important for reactions at low Q^2. Whereas in a mean-field calculation a nucleon experiences the presence of the others only through the mean-field generated by their mutual interaction, the random phase approximation additionally allows the particles to interact by means of the residual two-body force. The random phase approximation goes one step beyond this zeroth-order mean-field approach and describes a nuclear state as the coherent superposition of particle–hole contributions [4, 5].

$$|\Psi_{\rm RPA}\rangle = \sum_{c} \left\{ X_{(\Psi,C)} \; \left|ph^{-1}\right\rangle \; - \; Y_{(\Psi,C)} \; \left|hp^{-1}\right\rangle \right\} . \tag{8}$$

The summation index C stands for all quantum numbers defining a reaction channel unambiguously:

$$C = \{n_h, l_h, j_h, m_h, \varepsilon_h; l_p, j_p, m_p, \tau_z\} , \tag{9}$$

where the indices p and h indicate whether the considered quantum numbers relate to the particle or the hole state, ε_h denotes the binding-energy of the hole state and τ_z defines the isospin character of the particle–hole pair. The propagation of these particle–hole pairs in the nuclear medium is described by the polarization propagator. In our model, the continuum RPA equations are solved using a Greens function approach in which the polarization propagator is approximated by an iteration of the first-order contribution. The unperturbed wave-functions are generated using either a Woods–Saxon potential or a HF-calculation using a Skyrme force. The latter approach makes self-consistent HF-RPA calculations possible. As is shown in figure 3, long-range Random Phase Approximation correlations account for a considerable reduction of cross-sections at low incoming neutrino-energy [6].

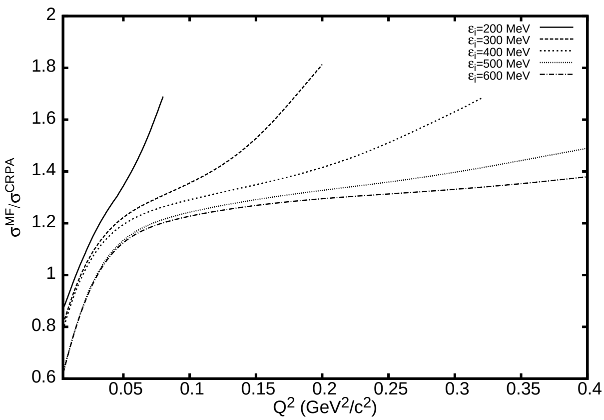

Fig. 3. Ratio of cross-sections obtained with mean field (MF) wave-functions to cross-sections including continuum RPA correlations (CRPA) as a function of Q^2 for incoming neutrino-energies ranging from 200 to 600 MeV and with ^{12}C as target nucleus.

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