Modeling neutrino-nucleus interactions in the few-GeV regime.

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Abstract.
Detecting neutrinos and extracting the information they bring along is an ambitious task that requires a detailed understanding of neutrino-nucleus interactions over a broad energy range. We present calculations for quasi-elastic neutrino-induced nucleon knockout reactions on atomic nuclei and neutrino-induced pion production reactions. In our models, final-state interactions are introduced using a relativistic multiple-scattering Glauber approximation (RMSGA) approach. For interactions at low incoming neutrino energies, long-range correlations are implemented by means of a continuum random phase approximation (CRPA) approach. As neutrinos are the only particles interacting solely by means of the weak interaction, they can reveal information about e.g. the structure of nuclei or the strange quark content of the nucleon that is difficult to obtain otherwise. We investigated these effects and present results for the sensitivity of neutrino interactions to the influence of the nucleon's strange quark sea.

1. Introduction

The experimental confirmation of neutrino oscillations raised an enormous experimental and theoretical interest in the oscillation properties of these particles. 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.

2. Quasi-elastic neutrino scattering

The one-fold differential cross section for the scattering process $A(\nu, lN)$ is given by

$$\frac{d\sigma}{dT_N} = \frac{M_N M_{A-1}}{(2\pi)^3 M_A} 4\pi^2 \int \sin\theta_l d\theta_l \int \sin\theta_N d\theta_N k_N f_{rec}^{-1} \sigma_M \left[v_L R_L + v_T R_T + h v_{T'} R_{T'} \right], \qquad (1)$$

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.

In Eq.(1), v_L, v_T and $v_{T'}$ are the longitudinal, transverse and interference kinematic factors and R_L, R_T and $R_{T'}$ the accompanying structure functions, reflecting the influence of nuclear

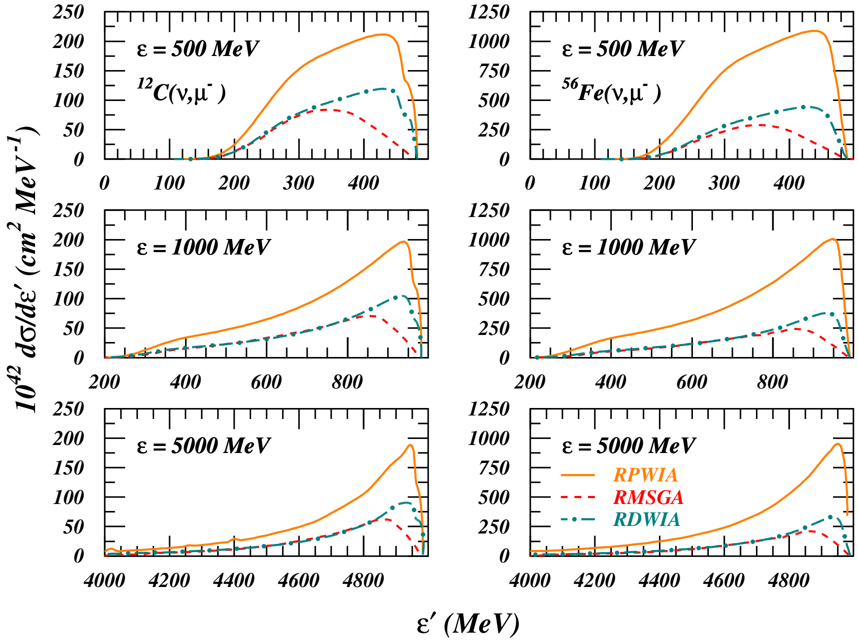

Figure 1. Cross sections for the charged-current reactions $^{12}\mathrm{C}(\nu_\mu, \mu^-)$ and $^{56}\mathrm{Fe}(\nu_\mu, \mu^-)$ as a function of the energy of the outgoing muon ε'. The different curves compare the RMSGA results (dashed) with the RDWIA (dash-dotted) and the RPWIA limit (full line).

dynamics on the scattering process [1]. The helicity of the incoming neutrino is denoted by h. In our numerical calculations, bound-state wave-functions are obtained within the Hartree approximation to the $\sigma - \omega$ model, adopting the W1 parametrization for the different field strengths.

We 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 rescattering 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 are 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 $\phi_F(\vec{r}) = \mathcal{G}[\vec{b}(x,y), z]\ \phi_{k_N,s_N}(\vec{r})$, 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) [1]. Figure 1 shows the influence 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.

3. Strangeness

The strangeness content of the nucleon influences neutrino-nucleus cross sections and has an important impact on several cross-section ratios. We compared the influence of axial as well as vector strangeness on ν and $\overline{\nu}$ cross-section ratios [3]. 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 for protons and neutrons, and on the longitudinal helicity asymmetry for neutrinos and antineutrinos. 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 $R_{NC/CC}$ ratios to strangeness effects is considerably smaller than that of $R_{p/n}$.

Whereas in PVES the smallness 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 parity-violating electron scattering and neutrino-induced processes would offer the best prospects for

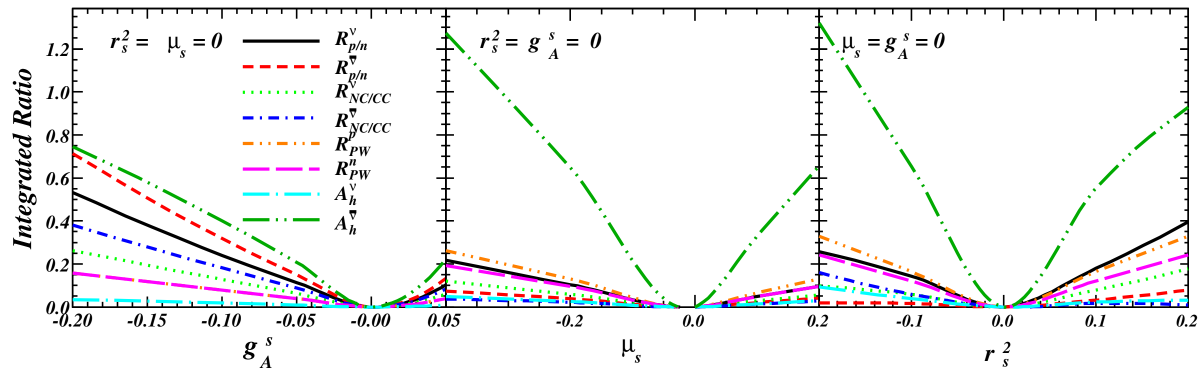

Figure 2. Comparison between the strangeness influence on various ratios of total cross-sections in terms of the relative sensitivity $\left|\frac{R(s=0)-R(s)}{R(s=0)}\right|$, as a function of the strangeness form factors g_A^s, μ_s and r_s^2 for 1 GeV neutrino scattering off ^{12}C.

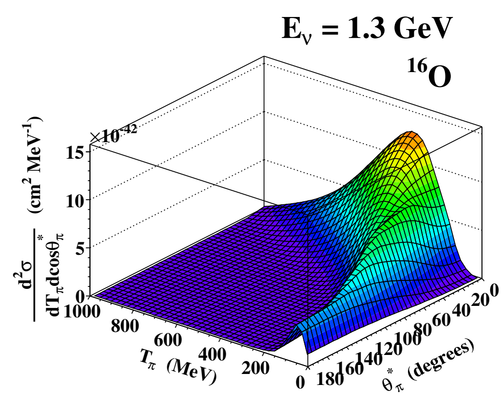

Figure 3. Resonant pion production off ^{16}O for 1.3 GeV incoming neutrinos.

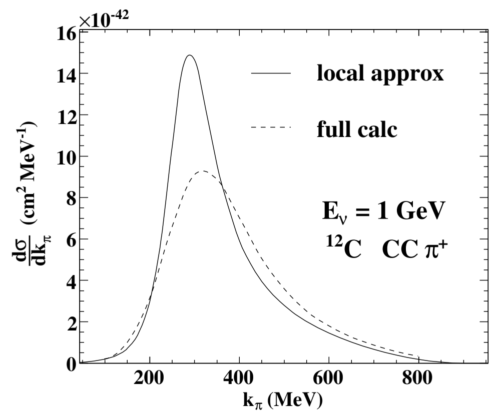

Figure 4. Comparison of full and local approximation calculations for coherent pion production.

a thorough understanding of the influence of the nucleon's strange quark sea on electroweak processes.

4. Weak one-pion production on a nucleus

At slightly higher energies, resonant and coherent pion production become important reaction channels. The Δ-mediated pion-production cross section is evaluated adopting the relativistic plane-wave impulse approximation for the calculation of the matrix element. The single particle wave functions are the same as those used in section 2. Medium modifications for the Δ were implemented as discussed in Ref. [4]. Figure 3 shows the differential cross section for neutrino-induced pion-production off ^{16}O.

Coherent pion production leaves the nuclear target intact by transferring only small four-momenta. Figure 4 compares full- and local-approximation calculations for charged-current coherent pion production on ^{12}C.

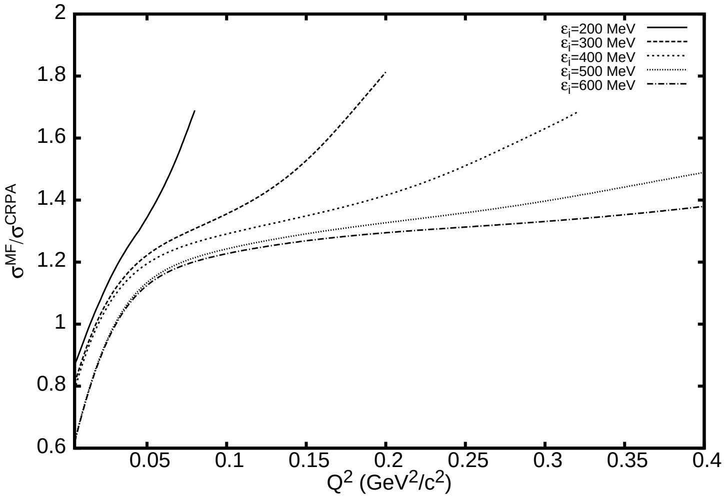

Figure 5. Ratio of cross sections obtained with mean field (MF) wave functions to cross sections including continuum RPA correlations (CRPA) as a function of Q^2 for incoming neutrino-energies ranging from 200 to 600 MeV and with ^{12}C as target nucleus.

5. Long-range CRPA correlations

For inclusive cross sections, especially at higher energies, the Fermi Gas model is remarkably accurate. At lower energies however, nuclear effects become preponderant. In a Random Phase Approximation (RPA) approach, long-range correlations between the nucleons in the nucleus are introduced. 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 describes a nuclear state as the coherent superposition of particle-hole contributions [5, 6].

$$|\Psi_{RPA}\rangle = \sum_{c} \left\{ X_{(\Psi,C)} \left|ph^{-1}\right\rangle - Y_{(\Psi,C)} \left|hp^{-1}\right\rangle \right\}. \tag{2}$$

The summation index C stands for all quantum numbers defining a reaction channel unambiguously. In our model, the continuum RPA equations are solved using a Green's 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 5, long-range Random Phase Approximation correlations account for a considerable reduction of cross sections at low incoming neutrino-energy.

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