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Theoretical update on low energy neutrino–nucleus reactions

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We review Quasielastic (QE) inclusive and semi–inclusive neutrino/antineutrino Charged Current (CC) and Neutral Current (NC) induced nuclear reactions at intermediate energies. We pay special attention to nuclear corrections besides Pauli blocking: Long and Short range nuclear correlations (RPA and SRC) and particle and hole Spectral Functions (SF). We also critically review the use of the Plane and Distorted Wave Impulse approximations (PWIA and DWIA) to describe inclusive one nucleon knockout reactions off nuclei. In this context, we present results from a Monte Carlo cascade method to account for the rescattering of the outgoing nucleon. Finally, we examine the effects of chiral non-resonant terms in neutrino pion production off the nucleon, and present some preliminary results on nuclear coherent pion production induced by neutrinos.

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1. Introduction

Neutrino physics is at the forefront of current theoretical and experimental research in astro, nuclear, and particle physics. The presence of neutrinos, being chargeless particles, can only be inferred by detecting the secondary particles they create when colliding and interacting with matter. Nuclei are often used as neutrino detectors, thus the interpretation of neutrino data heavily relies on detailed and quantitative knowledge of the features of the neutrino-nucleus interaction. At low and intermediate energies, the neutrino-nucleus cross section is dominated by QE and single pion production processes. Those processes are largely dominated by mechanisms where the gauge boson ($W^\pm, Z^0$) inside the nuclear medium is absorbed by one nucleon, or excites a $\Delta(1232)$ resonance which subsequently decays into a $N\pi$ pair, respectively. There is a general consensus among the theorists that a simple Fermi Gas (FG) model, widely used in the analysis of neutrino oscillation experiments, fails to provide a satisfactory description of the measured cross sections, and inclusion of further nuclear effects is needed [1]. In the first part of the talk, I will focus on the most relevant nuclear ingredients affecting to QE inclusive and semi-inclusive processes. Next, I will examine the structure of the neutrino pion production off the nucleon amplitude, and the role played by chiral symmetry.

2. QE Inclusive and Semi-Inclusive Reactions

The double differential cross section, with respect to the outgoing lepton kinematical variables, for the process $\nu_l(k) + A_Z \to l^-(k') + X$ is given in the Laboratory (LAB) frame by[1]

$$\frac{d^2\sigma_{\nu l}}{d\Omega(\hat{k}')dE'_l} = \frac{|\vec{k}'|}{|\vec{k}\,|}\frac{G^2}{4\pi^2}L_{\mu\sigma}W^{\mu\sigma} \tag{2.1}$$

with $\vec{k}$ and $\vec{k}'$ the LAB lepton momenta, G the Fermi constant and L and W the leptonic and hadronic tensors, respectively. The hadronic tensor includes all sort of non-leptonic vertices and is determined by the W^+-boson selfenergy, $\Pi_W^{\mu\rho}(q)$, in the nuclear medium. We follow here the formalism of Ref. [4], and we evaluate the selfenergy of a neutrino moving in infinite nuclear matter of density ρ. We obtain,

$$W_s^{\mu\sigma}(q) \propto \Theta(q^0)\int\frac{d^3r}{2\pi}\,\mathrm{Im}\left[\Pi_W^{\mu\sigma}+\Pi_W^{\sigma\mu}\right](q;\rho(r)) \tag{2.2}$$

$$W_a^{\mu\sigma}(q) \propto \Theta(q^0)\int\frac{d^3r}{2\pi}\,\mathrm{Re}\left[\Pi_W^{\mu\sigma}-\Pi_W^{\sigma\mu}\right](q;\rho(r)) \tag{2.3}$$

with $W^{\mu\sigma} = W_s^{\mu\sigma} + \mathrm{i}W_a^{\mu\sigma}$, $q = k - k'$, and where we have used the Local Density Approximation (LDA), which assumes a FG model for the nucleus to start with[2]. The virtual W gauge boson can

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[1] Extensions to antineutrino or NC induced processes are straightforward. Details can be found in Refs. [2, 3].

[2] Large basis shell model schemes provides a very accurate description of the nuclear ground state wave functions [5], which is unnecessary when one is dealing with inclusive processes and nuclear excitation energies above, let us say, 50 MeV [6]. Besides, the description of high-lying excitations necessitates the use of large model spaces and this often leads to computational difficulties, making the approach applicable essentially only for neutrino energies in the range of tens of MeV.

be absorbed by one nucleon, 1p1h nuclear excitation, leading to the QE contribution to the nuclear response function. In this case, the $W-$selfenergy is determined, besides the $W^{\pm}NN$ vertex, by the imaginary part of isospin asymmetric Lindhard function. We work on an non-symmetric nuclear matter with different Fermi sea levels for protons than for neutrons. Explicit expressions can be found in [2]. In what follows, we will consider further improvements on this simple framework:

- We enforce a correct energy balance of the different studied processes and consider the effect of the Coulomb field of the nucleus acting on the ejected charged lepton.
- RPA and SRC: We take into account polarization effects by substituting the particle-hole (1p1h) response by an RPA response consisting of a series of ph and Δh excitations. We use a Landau-Migdal ph-ph interaction [7]: $V = c_0\,\{f_0 + f_0'\vec{\tau}_1\vec{\tau}_2 + g_0\vec{\sigma}_1\vec{\sigma}_2 + g_0'\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2\}$. In the vector-isovector channel ($\vec{\sigma}\vec{\sigma}\vec{\tau}\vec{\tau}$ operator) we use an interaction [4] with explicit $\pi-$meson (longitudinal) and $\rho-$meson (transverse) exchanges, that also includes SRC and $\Delta(1232)$ degrees of freedom. RPA effects are extremely important, as confirmed by several groups [8], and should be definitely taken into account in any neutrino oscillation analysis [9]. As a matter of example, we show in the left panel of Fig. 1 results in ^{16}O at intermediate energies [2].
- SF+FSI: We take into account the modification of the nucleon dispersion relation in the medium by using nucleon propagators properly dressed with a realistic self-energy [10]. Thus, we compute the imaginary part of the Lindhard function (ph propagator) using realistic particle and hole SF's. The effect is twofold, firstly by using the hole SF, we go beyond a simple FG of non-interacting nucleons, and we include some interactions among the nucleons. Secondly, the particle SF accounts for the interaction of the ejected nucleon with the final nuclear state; this is most commonly called Final State Interaction (FSI) in the literature. We show some results in the left panel of Fig. 1, taken from Ref. [2]. We find a sizeable reduction of the strength at the QE peak, which is slightly shifted, and an enhancement of the high energy transfer tail. For integrated cross sections both effects partially compensate. We find a qualitative and quantitative agreement with the results of Benhar et al. [1] and of the Giessen group [11].

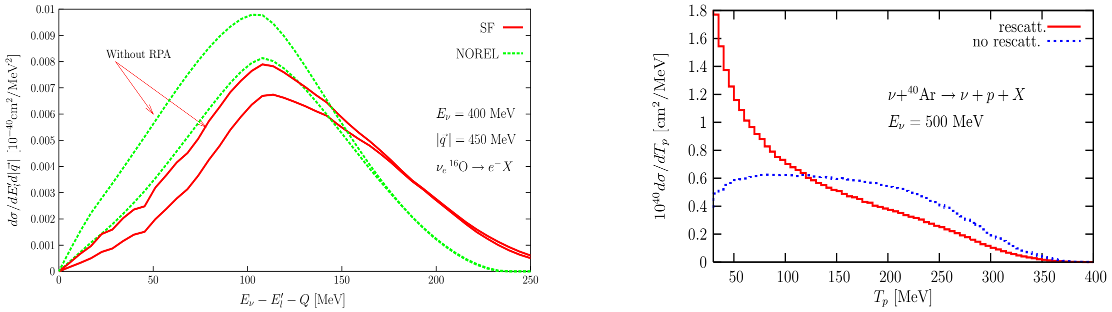

Figure 1: Left: ν_e inclusive QE differential cross sections in ^{16}O as a function of the transferred energy, for a fixed transferred momentum. We show results with and without RPA and SRC and with (SF) and without (NOREL) SF+FSI effects. Right: $^{40}Ar(\nu,\nu+p)$ cross section as a function of the kinetic energy of the final proton. The dashed histogram shows results without rescattering (PWIA) and the solid one has been obtained from a MC cascade simulation.

We have estimated the theoretical uncertainties of our model by Monte Carlo (MC) propagating the uncertainties of its different inputs into differential and total cross sections [12]. We conclude that our approach provides QE $\nu(\bar\nu)$–nucleus cross sections with relative errors of about 10-15%, while uncertainties affecting the ratios $\sigma(\mu)/\sigma(e)$ and $\sigma(\bar\mu)/\sigma(\bar e)$ would be certainly smaller, not larger than about 5%, and mostly coming from deficiencies of the local FG picture of the nucleus [12].

Finally in the QE region, we have also studied CC and NC nucleon emission processes which play an important role in the analysis of oscillation experiments. In particular, they constitute the unique signal for NC neutrino driven reactions. We use a MC simulation method to account for the rescattering of the outgoing nucleon [4]. The first step is the gauge boson ($W^\pm$ and Z^0) absorption in the nucleus[3]. Different distributions for both NC and CC processes can be found in [3], as example, we show here results for NC nucleon emission from argon (right panel of Fig. 1). The rescattering of the outgoing nucleon produces a depletion of the high energy side of the spectrum, but the scattered nucleons clearly enhance the low energy region. Our results compare well with those of Ref. [11] obtained by means of a transport model.

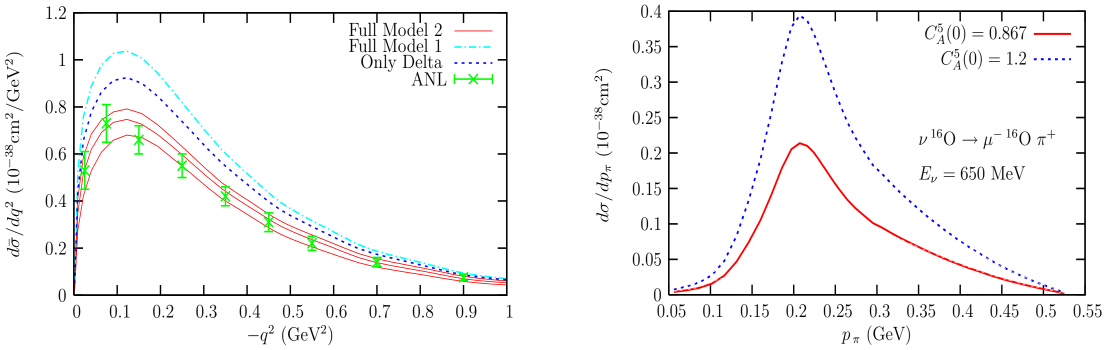

Figure 2: Left: Flux averaged πN invariant mass distribution of events for the $\nu_\mu p \to \mu^- p \pi^+$ reaction. Dashed lines stand for the contribution of the Δ pole term with $C_5^A(0) = 1.2$ (GTR) and $M_{A\Delta} = 1.05$ GeV. Dashed–dotted and central solid lines are obtained when the full model of Ref. [13] is considered with $C_5^A(0) = 1.2$, $M_{A\Delta} = 1.05$ GeV (dashed-dotted) and with the best fit parameters $C_5^A(0) = 0.867$, $M_{A\Delta} = 0.985$ GeV (solid). For this latter case, we also show the 68% CL bands. Right: CC coherent pion production differential cross section.

3. Chiral Symmetry and Neutrino Pion Production off the Nucleon

The neutrino pion production off the nucleon is traditionally described in the literature by means of the weak excitation of the $\Delta(1232)$ resonance and its subsequent decay into $N\pi$. Here,

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[3] Some calculations in the literature use the PWIA and DWIA, including or not relativistic effects. The PWIA constitutes a poor approximation, since it neglects all types of interactions between the ejected nucleon and the residual nuclear system. The DWIA describes the ejected nucleon as a solution of the Dirac or Schrödinger equation with an optical potential obtained by fitting elastic proton–nucleus scattering data. The imaginary part accounts for the absorption into unobserved channels. This scheme is incorrect to study nucleon emission processes where the state of the final nucleus is totally unobserved, and thus all final nuclear configurations, either in the discrete or on the continuum, contribute. The distortion of the nucleon wave function by a complex optical potential removes all events where the nucleons collide inelastically with other nucleons. Thus, in DWIA calculations, the nucleons that interact inelastically are lost when in the physical process they simply come off the nucleus with a different energy, angle, and maybe charge, and they should definitely be taken into account.

we present results from a model [13] that includes also some background terms required by chiral symmetry. The contribution of these terms is sizeable and leads to significant effects in total and partially integrated pion production cross sections at intermediate energies. We re-adjust the $C_5^A(q^2)$ form–factor, that controls the largest term of the $\Delta-$axial contribution, and find corrections of the order of 30% to the off diagonal Goldberger-Treiman relation (GTR), when the $\nu_\mu p \to \mu^- p\pi^+$ ANL q^2-differential cross section data [14] are fitted (right panel of Fig. 2). Thus, we find a substantially smaller contribution of the Δ pole mechanism than in other approaches [15], which has an important effect on the CC and NC nuclear coherent pion production cross sections (Fig. 2). We have also extended the model to describe two pion production processes near threshold [16].

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