Nucleon Emision Off Nuclei Induced By Neutrino Interactions

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Abstract. We make a review of the main nuclear effects that affect neutrino-nucleus cross sections. We discuss how the different models in the literature try to describe these different effects, and thus try to compare between them. We focus on the quasi-elastic reaction in the neutrino energy region of around 1 GeV, where recent data from MiniBoone are available. Among the issues discussed are the different treatment of medium corrections to initial and final state nucleon wave functions and the problem of the rescattering of ejected nucleons.

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INTRODUCTION

The study of neutrinos is playing a very relevant role in current research in nuclear, astro and particle physics. One of these major topics is neutrino oscillations, that since its discovery 10 years ago by the Super Kamiokande collaboration [1, 2] have evolved and is now reaching the realm of precision experiments [3]. This new generation of precision experiments is no longer hindered by statistical error, but is dominated by systematic uncertainties, one of the most important of these systematic errors being the neutrino-nucleus cross section. However neutrinos are a neutral, weakly interacting particle, thus its detection must rely on the observation of secondary particles that appear after the scattering of the incoming neutrino with one of the nuclei of the passive part of the detector set up. The study of neutrino oscillation physics requires a good determination of the incoming neutrino energy. However accelerator neutrino beams are produced by the muon decay, thus being far from monochromatic. The determination of the energy of a detected neutrino and the nature of the collision thus can be only done through kinematic reconstruction from the produced particles.

A proper knowledge of the neutrino-nucleus cross sections is therefore required for the experiment analysis. Nevertheless most of the codes and models used for the modelling of these processes in the analysis of experimental data are based on Fermi Gas models, namely the famous Marteau model [4]. However most of these models are known from the experience on electron scattering physics to fail to describe the existing experimental data.

These reasons have motivated the interest of the theoretical nuclear physics community on the subject of neutrino-nucleus scattering. There is a general consensus among the community that a simple Fermi Gas model, widely used in the analysis of neutrino oscillation experiments, is no longer good enough for the level of precision required for neutrino experiments. Thus many different approaches has been proposed to model these reactions. In this talk I will describe the main nuclear physics effects that, based on the experience from electron scattering physics, are expected to arise. We will also try to review a few of the proposed nuclear models. For the sake of simplicity we will focus on the quasi-elastic reactions at neutrino energies from a few hundred MeV to around 1 GeV which are of interest to MiniBoone and T2K. Of course at these experiments pion production processes play an important role, however the pion physics involved in these processes is somewhat beyond the scope of this contribution. For a more general look at this neutrino interactions issues please look at the contribution of L. Alvarez Ruso in this same proceedings [5].

NUCLEAR EFFECTS IN INCLUSIVE PROCESSES

In this section we introduce a model for the quasi-elastic inclusive charged current process

$$\nu_l + {}^Z A \rightarrow l^- + X \tag{1}$$

where the only detected particle being the outgoing lepton and therefore one must sum over all possible final hadron states, here denoted by X. In the case of neutral current processes the outgoing lepton part is a neutrino. So in order to get information about the process some of the hadronic products must be detected, be it a nucleon (usually proton) or pion. The residual nucleus is not detected in the Cerenkov radiation experiments so a sum over nuclear states is also needed, what is usually called semi-inclusive observables. In this talk we will focus in the situation where the only detected hadron is a nucleon. If we were to include also pions we should take into account the production of pions in the primary ν-nucleon vertex. We will follow the model of references [6] and [7] which start from a local density Fermi Gas model, but in top of it they include a whole lot of nuclear effects. We will refer as this model as the Valencia-Granada model. Actually this model is actually based on a previous work dealing with electron scattering [8] that was able to reasonably describe the available experimental data.

Due to the difficult nature of neutrino cross sections experiments (that sometimes rely on some neutrino interaction model), it is very important to validate any neutrino-nucleus interaction model against electron-nucleus scattering experiments. As can be seen in Fig.1 the electron version of the Valencia-Granada model describes rather well the existing experimental data. In this figure we can observe the main features of this kind of reactions. A large broad peak at low transfered energy ω (the quasi-elastic peak), and a second lower peak that is associated with the $\Delta(1232)$ production. A major feature of this model is that it is able to correctly describe the region between the two major peaks. This *gap* region is underestimated by most models, as they usually do not take into account any process beyond the dominant absorption by one nucleon (quasi-elastic) and delta production. However one must notice the existence of additional processes like non-resonant pion production and boson absorption by two nucleons. Thus in order to properly describe inclusive processes it is clearly needed the inclusion of additional non-resonant mechanisms. The first step towards the inclusion this processes in the framework of a model of neutrino-nucleus scattering is having an adequate model for neutrino-nucleon scattering in free space (that is, with no nuclear medium effects). Many interesting approaches are being developed to tackle this problem, see *e.g.* Ref.[9].

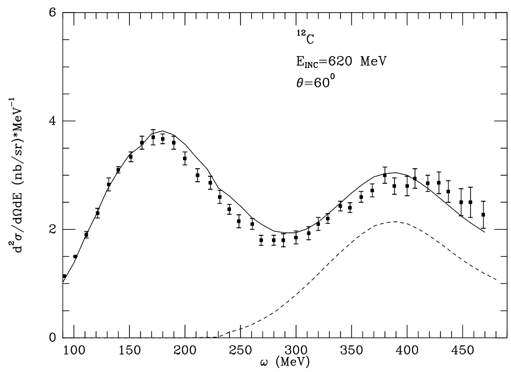

Figure 1. Double differential cross section for the inclusive process $e^- + C^{12} \rightarrow e^- + X$. Picture taken from [8]

The differential cross section for the neutrino collision can be written

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

with L and W the leptonic and hadronic tensors, respectively. The leptonic tensor is well known and is obtained from the weak interaction in the Fermi contact approximation. On the other hand, the inclusive CC nuclear cross section is related to the imaginary part of the neutrino self-energy in the medium by:

$$\sigma = -\frac{1}{|\vec{k}|}\int d^3\vec{r}\,\mathrm{Im}\Sigma_\nu(k;\rho(r)) \tag{3}$$

We obtain the imaginary part of the neutrino self-energy in the medium $\mathrm{Im}\Sigma_\nu$ by means of the Cutkosky's rules. We obtain for $k^0 > 0$

$$\mathrm{Im}\Sigma_\nu(k) = \frac{8G}{\sqrt{2}M_W^2}\int\frac{d^3k'}{(2\pi)^3}\frac{\Theta(q^0)}{2E'_l}\,\mathrm{Im}\left\{\Pi_W^{\mu\nu}(q;\rho)L_{\nu\mu}\right\} \tag{4}$$

and thus, the hadronic tensor is basically an integral over the nuclear volume of the W-boson self-energy $\Pi_W^{\mu\nu}(q;\rho)$ inside the nuclear medium. In general we can then take into account the different in-medium effects and reaction mechanism modes (W absorption by one nucleon or by a pair of nucleons, pion production, resonance excitation…) by including the correspondent diagrams in the W self-energy diagram. We will focus in the charged current quasi-elastic process, that corresponds to the W absorption by one nucleon. In general we obtain that the hadron tensor can be expressed (up to some constant) as:

$$W^{\mu\nu} = \int d^3\vec{r}\int\frac{d^3\vec{p}}{(2\pi)^3}\int_{\mu-q^0}^{\mu} d\omega A^{\nu\mu}(p,q)|_{p^0=\bar{E}(\vec{p})} \\ S_h(\omega,\vec{p};\rho)\,S_p\left(q^0+\omega,\vec{p}+\vec{q};\rho\right). \tag{5}$$

In this expression the tensor $A^{\nu\mu}$ contains all the information related to the neutrino-nucleon interaction. The S_p and S_h are the particle and hole nucleon spectral functions and contain the information on the nucleon wave functions in the final and initial nuclear state respectively. μ is the chemical potential. In a simple local density Fermi Gas the nucleons are on mass shell and thus the hole spectral functions take the very simple form:

$$S_h(\omega,\vec{p};\rho) = \delta(\omega - E(\vec{p}))\Omega(E_F - E(\vec{p})) \qquad (6)$$

and an analogue expression for the particle one. This expression leads to a description that is completely equivalent to the usual Fermi gas model used in the literature. The only nuclear physics effects that are taken into account are the Pauli blocking effect (see the Θ function) and the Fermi motion of the nucleons, whose momenta are approximated to be distributed uniformly.

However, this is well known to be an oversimplificated model for the electron scattering process, and we expect it to be so also for the neutrino process. Thus we improve our model by including realistic spectral functions,

$$S_{p,h}(\omega,\vec{p};\rho) = \mp\frac{1}{\pi}\frac{\mathrm{Im}\Sigma(\omega,\vec{p};\rho)}{[\omega-\bar{E}(\vec{p})-\mathrm{Re}\Sigma(\omega,\vec{p};\rho)]^2+[\mathrm{Im}\Sigma(\omega,\vec{p};\rho)]^2} \qquad (7)$$

with $\omega \geq \mu$ or $\omega \leq \mu$ for S_p and S_h, respectively. The chemical potential μ is determined by

$$\mu = M + \frac{k_F^2}{2M} + \mathrm{Re}\Sigma(\mu, k_F) \qquad (8)$$

where in Valencia-Granada model the reference [10] was followed for the nucleon self-energy $\Sigma(\mu,k_F)$. Notice that both particle and hole self-energies are included in this approach, in contrast with other models in the literature that only include the effect of nucleon wave functions in the hole states. It is also very important to notice how in the limit $\Sigma \to 0$ we recover the expressions of a non-interacting Fermi Gas model. This is an obvious point that should be tested in all models for lepton scattering off nuclei. The effect of particle (that is final state nucleons) spectral functions is often defined in the literature as final state interactions (FSI). This effect (see Fig.2) usually produces a broadening of the nuclear response and a reduction of the response at the peak, however the total response is not much affected, specially when RPA corrections (see next paragraph) are also taken into account.

Furthermore the excited nuclear states are expected to be correlated by means of the nucleon-nucleon interaction. We model this effect by including a series of particle-hole excitations, see Fig.3, of the RPA type. The

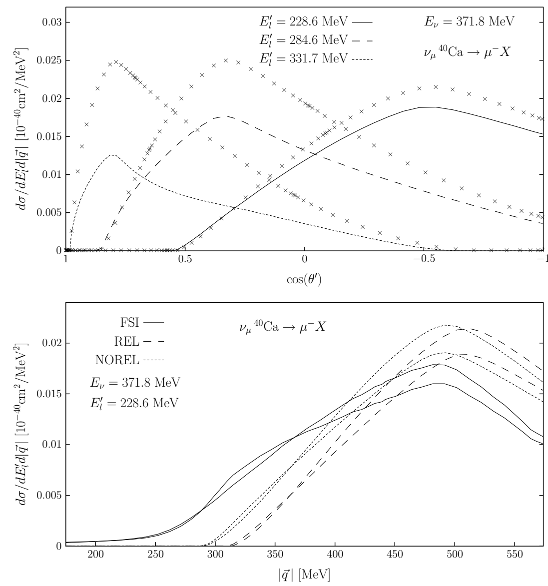

Figure 2. ν_e and $\bar{\nu}_e$ inclusive quasi-elastic cross sections in oxygen as a function of the transferred energy, at two values of the transferred momentum. We show results for relativistic (REL) and non-relativistic nucleon kinematics. In this latter case, we present results with (FSI) and without (NOREL) FSI effects. For the three cases, we also show the effect of taking into account RPA correlations (lower lines at the peak). See Ref. [6] for further details.

inclusion of this diagrams modify the expression for the tensor $A^{\nu\mu}$ and induces a reduction of the cross section, specially at low Q^2 kinematics. We use an effective Landau-Migdal $ph-ph$ interaction where in the vector-isovector channel ($\vec{\sigma}\cdot\vec{\sigma}\vec{\tau}\cdot\vec{\tau}$ operator) we use an interaction with explicit π meson (longitudinal) and ρ meson (transverse) exchanges that also includes $\Delta(1232)$ degrees of freedom.

This point has been applied in [11] to the MiniBoone experiment [12] following the prescriptions of our model. In this reference it was found that the inclusion of this RPA correlations improves the description of the cross section measurements in the MiniBoone experiment, without including unphysical parameters, like effective Fermi momentum…

SEMI-INCLUSIVE OBSERVABLES: NUCLEON RESCATTERING

In the previous section we have focused in processes where the only detected particle is the outgoing (charged) lepton. However sometimes more information from the process is obtained from hadrons. Actually these are the only possible particles to be detected in neutral current processes. In this process a new effect must be taken

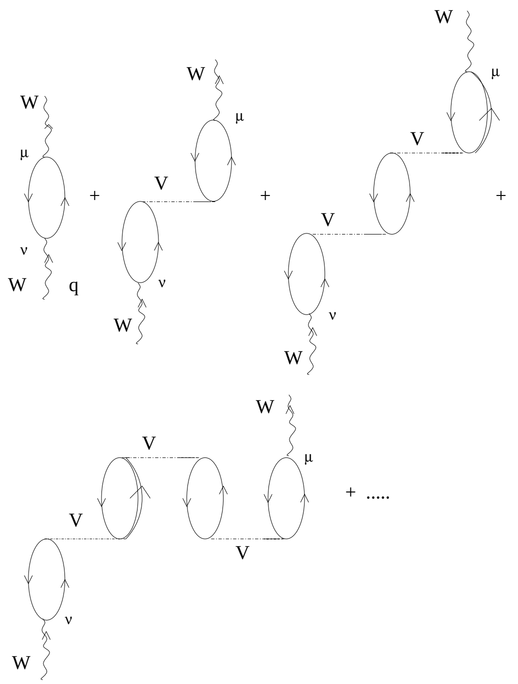

Figure 3. Set of irreducible diagrams responsible for the polarization (RPA) effects in the $1p1h$ contribution to the W self-energy.

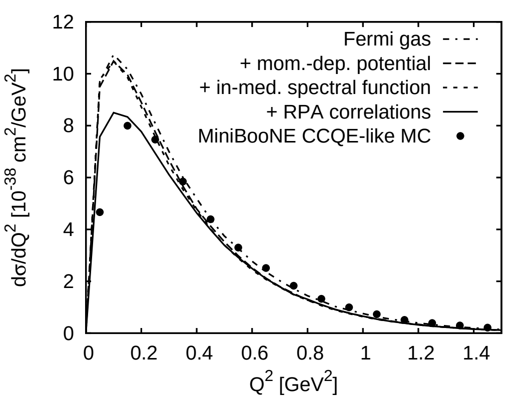

Figure 4. Taken from Ref. [13].

into account in top of the ones described in the previous section. This is the rescattering of outgoing hadrons in its way out of the nucleus. Actually in the previous model the nucleon that interacts with the neutrino is put on mass shell and goes out of the nucleus. However it is well known that this nucleon strongly interacts with the other nucleons in the medium and can be deflected, inducing the emission of secondary nucleons or, given enough energy, pions. Of course this new processes do not change the total inclusive cross section as described in the previous section. However in the case of neutral currents it is necessary to properly describe this processes as secondary particle emission processes can result in background events, *e.g.* π^0 decay photons can mimic Cerenkov radiation from electrons, or in other processes energy can be transfered to undetected neutrons thus introducing problems in the incoming neutrino kinematics reconstruction. For that reason it is very important to properly model this rescattering processes. A few different approaches have been proposed to describe this:

1. Distorted wave impulse approximation. In this models the outgoing nucleon wave function is calculated using a wave equation complex potential. The imaginary part of this potential removes all the events where the outgoing nucleon collides. This approach is fully quantum mechanical, however it has the major disadvantage that is only suitable to deal with fully exclusive observables where the final nuclear state is also observed. These is because the optical potential is not unitary and thus it does not shuffle events from one channel to another (as should be done when dealing with semi-inclusive observables) but just remove those events where the nucleon undergoes a collision,changing its kinematics. For that reason it is well known that this approach underestimates cross sections in semi-inclusive reactions.
2. Monte Carlo cascade models. This is the usual approach in which the trajectory of the ejected hadrons is simulated via a semi-classical Monte Carlo algorithm that takes into account changes of energy and momentum of the emitted nucleon, as well as the possibility of having secondary hadrons.
3. Transport model. Recently a new approach has been proposed by the Giessen group [14]. In this approach the semi-classical transport equations are explicitly solved for all ejected hadrons, thus allowing for a rigorous tracking of all particles.

In the following we shall focus on the model by the Valencia-Granada group [7], which is a Monte Carlo cascade like model. We shall use a simplified version of the model where pion production processes are not included. In this model for any given leptonic kinematic q^μ, a point $(\vec{r})$ in the nucleus is randomly selected where the gauge boson absorption takes place according to the profile $d^5\sigma/d\Omega' dE' d^3\vec{r}$. Then a nucleon with a random momentum is picked up from the Fermi sea with a given momentum $\vec{p}$. Its kinematics is determined via energy conservation

$$E = q^0 + \sqrt{\vec{p}^2 + M^2} \qquad (9)$$

and Pauli blocking effects are explicitly included. The nucleon is assumed to be in an average nucleon potential $V(r) = k_F^2(\vec{r})/2M$ and then it is moved in discrete steps until it leaves the nucleus. At each of these steps the

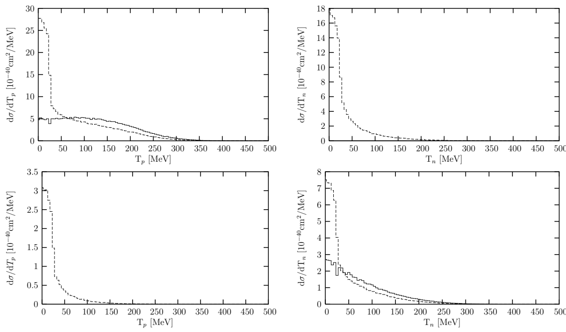

Figure 5. Charged current $^{40}Ar(\nu,\mu^- + N)$ (upper panels) and $^{40}Ar(\bar{\nu},\mu^+ + N)$ (lower panels) cross sections as a function of the kinetic energy of the final nucleon. Left and right panels correspond to the emission of protons and neutrons respectively. The solid histogram shows results without FSI and the dashed one the full model. Please look Ref. [7] for further details.

possibility of producing a secondary nucleon is explicitly taken into account by means of the cross section

$$\hat{\sigma}^{N_1N_2} = \int d\Omega_{CM} \frac{d\sigma^{N_1N_2}}{d\Omega_{CM}} C_T(q,\rho)\Theta\left(\kappa - \frac{|\vec{p}\cdot\vec{p}_{CM}|}{|\vec{p}||\vec{p}_{CM}|}\right) \tag{10}$$

where in-medium renormalization of the nucleon-nucleon interaction ($C_T(q,\rho)$) and Pauli blocking effects $\Theta(\kappa - |\vec{p}\cdot\vec{p}_{CM}|\ |\vec{p}||\vec{p}_{CM}|)$ are explicitly included.

The effect of this cascade algorithm in the spectra of outgoing nucleons can be easily appreciated in Fig.5. The nucleons spectra produced by CC processes induced by muon neutrinos are shown in Fig. 5 for Argon. Of course neutrinos only interact via CC with neutrons and would emit protons, but these primary protons interact strongly with the medium and collide with other nucleons which are also ejected. As a consequence there is a reduction of the flux of high energy protons but a large number of secondary nucleons, many of them neutrons, of lower energies appear.

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