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# Neutrino Cross Sections and Oscillation Parameters

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**Abstract**

The quantitative understanding of how the description of nuclear dynamics affects the neutrino-nucleus cross sections—needed to reduce the systematic uncertainty of long baseline neutrino oscillation experiments—involves severe difficulties. In this paper, I review the status and prospects of theoretical studies of neutrino-nucleus interactions, and briefly discuss the influence of the treatment of nuclear effects on the determination of oscillation parameters.

*Keywords:* Lepton-nucleus scattering, Charged current interaction, Determination of neutrino oscillation parameters

## 1. Introduction

Experimental searches of neutrino oscillations exploit neutrino-nucleus interactions to infer the properties of the beam particles, which are largely unknown. The use of nuclear targets as detectors, while allowing for a substantial increase of the event rate, entails non trivial problems, since the interpretation of the observed signal requires that neutrino interactions with atomic nuclei be under control at quantitative level. Given the present experimental accuracy, the treatment of nuclear effects is in fact acknowledged as one of the main sources of systematic uncertainty [1].

Over the past decade, it has become more and more evident that the independent particle model of nuclei—the crudest implementation of which is the Relativistic Fermi Gas Model (RFGM) routinely employed in simulations of neutrino-nucleus interactions—fails to account for the complexity of nuclear dynamics and the variety of reaction mechanisms contributing to the detected signals.

A great deal of effort is currently being devoted to the development of theoretical models providing a fully quantitative description of the neutrino-nucleus cross section in the kinematical regime relevant to most ongoing and future accelerator-based experiments, corresponding to neutrino energies ranging from few hundred MeV to few GeV. In this context, a key role is played by the availability of a wealth of electron scattering data, that can be used to validate the new models.

In this paper, I review the present status of understanding of neutrino-nucleus interactions, and report the results of pioneering analyses aimed at establishing a connection between nuclear modelling and the determination of oscillation parameters.

## 2. Neutrino energy reconstruction

Nuclear effects impact every step of data analysis, from event identification to the determination of oscillation parameters.

Consider, for simplicity, two neutrino flavours. The probability that a neutrino of flavour $\alpha$ oscillate to flavour $\beta$ after travelling a distance $L$ is given by

$$P_{\alpha\to\beta} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) , \tag{1}$$

where $\theta$ and $\Delta m^2$ are the mixing angle and the squared mass difference, respectively. The above equation clearly shows that the neutrino energy, $E_\nu$, plays a critical role in the determination of $\Delta m^2$.

Let us focus on charged current (CC) quasi elastic (QE) interactions of muon neutrinos, leading to the single-nucleon knockout process

$$\nu_\mu + n \to \mu^- + p , \tag{2}$$

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which provides the dominant contribution to the cross section at energies ranging from few hundreds MeV to $\sim$ 1 GeV. In this channel, the neutrino energy can be easily obtained from the requirement

$$(p_\nu + k_n - p_\mu)^2 = m_p^2 \ , \tag{3}$$

where $p_\nu \equiv (E_\nu, \mathbf{p}_\nu)$, $p_\mu \equiv (E_\mu, \mathbf{p}_\mu)$ and $k_n \equiv (E_n, \mathbf{k}_n)$ are the neutrino, muon and neutron four momenta, respectivelt, and $m_p$ denotes the proton mass. The resulting expression is

$$E_\nu = \frac{m_p^2 - m_\mu^2 - {E_n}^2 + 2E_\mu E_n - 2\mathbf{p}_\mu \cdot \mathbf{k}_n + |{\mathbf{k}_n}^2|}{2(E_n - E_\mu + |\mathbf{p}_\mu| \cos\theta_\mu - |\mathbf{k}_n| \cos\theta_n)} . \tag{4}$$

The above equation shows that the reconstruction of $E_\nu$ requires the knowledge of both the *measured* kinematical variables of the outgoing charged lepton, i.e. its momentum $\mathbf{p}_\mu$, energy $E_\mu = (\mathbf{p}_\mu^2 + m_\mu^2)^{1/2}$ and scattering angle $\theta_\mu$, and the momentum and energy of the interacting neutron *bound* in the target nucleus, $\mathbf{k}_n$ and $E_n$. Existing analyses routinely set $|\mathbf{k}_n| = 0$ and $E_n = m_n - \epsilon$, where $m_n$ is the neutron mass and $\epsilon$ is an average binding energy, tipically $\sim$ 20 MeV in carbon and oxygen [2].

The momentum and energy distribution of bound neutrons, described by the spectral function $P(|\mathbf{k}_n|, E)$, has been extensively studied, both experimentally and theoretically. The spectral function of oxygen, obtained in Ref. [3] combining the data collected by $(e, e'p)$ experiments and the results of theoretical calculations based on a realistic model of nuclear dynamics, is shown in Fig. 1. While the peaks corresponding to the shell model states, broadened by residual interactions, can be easily recognised, it clearly appears that a significant fraction of the strength, about 20 %, is pushed to large momentum and energy by nucleon-nucleon correlations.

Figure 2 illustrates the neutrino energy distribution $F(E_\nu)$, computed from Eq. (4) using values of $|\mathbf{k}_n|$ and $E_n$ sampled from the probability distribution $|\mathbf{k}_n|^2 P(|\mathbf{k}_n|, E)$ with the spectral function of Ref. [3]. The polar and azimuthal angles specifying the direction of the neutron momentum have been assumed to be uniformly distributed. The resulting neutrino energy distribution turns out to be broad, its tail extending to very large values of $E_\nu$ being a reflection the correlation tails of $P(|\mathbf{k}_n|, E)$.

## 3. The lepton-nucleus cross section

The Impulse Approximation (IA) scheme, extensively employed to analyse electron-nucleus scattering

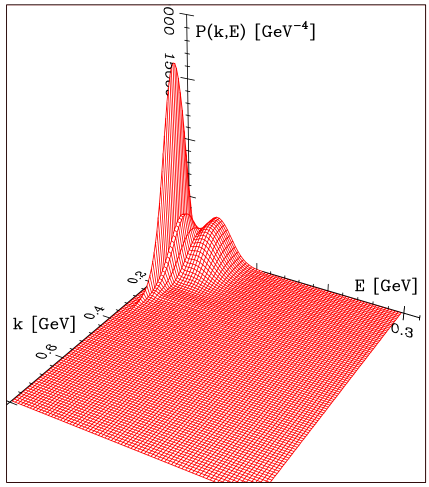


Figure 1: Spectral function describing the energy and momentum distribution of a proton bound in the oxygen ground state [3].

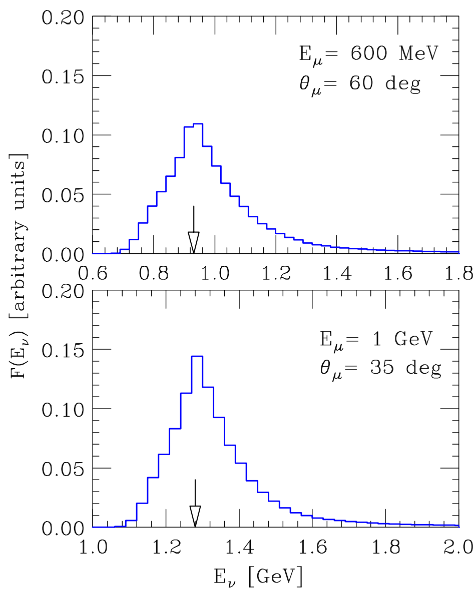


Figure 2: Reconstructed neutrino energy distribution at muon energy and scattering angle $E_\mu$ = 600 MeV and $\theta_\mu$ = 60 deg (upper panel) and $E_\mu$ = 1 GeV and $\theta_\mu$ = 35 deg (lower panel), obtained from Eq. (4) using 2 $\times 10^4$ pairs of $(|\mathbf{k}_n|, E)$ values sampled from the probability distributions associated with the oxygen spectral function of Ref.[3]. The arrows point to the values of $E_\nu$ obtained setting $|\mathbf{k}_n|$ = 0 and $E_n = m_n - \epsilon$, with $\epsilon$ = 27 MeV.