Study of Neutrino Cross-Sections and Nuclear Model

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The probability of neutrino oscillations is governed by the neutrino oscillation formula:

$$P_{\alpha\rightarrow\beta} = \sin^2(2\theta) sin^2\left(\frac{\Delta m^2 L}{4E}\right) \tag{1}$$

Accurate and precise knowledge of the ν cross-section, and of the related observables, plays an important role in the next generation of experiments. Various target nuclei, like C, O, Fe, Ar, Pb, . . . , are normally (and presumably will continue to be) employed to provide the detector mass. The cross-section of neutrino interactions with both nucleons and nuclei is usually written in the form $\sigma_{tot} = \sigma_{QEL} + \sigma_{RES} + \sigma_{DIS}$.where the first term refers to quasi elastic scattering and the second and third terms refer respectively to the resonant excitation channel and DIS. The quasi-elastic scattering reaction is characterized by low Q^2 and invariant mass of the produced hadronic state $W = M_p$. The dynamics of QE interactions can be described by a V-A current Lagrangian [1]. The hadronic current is usually defined through the nucleon vector Form Factors, determined from electron scattering experiments, and the axial Form Factor, assumed to be of dipole form, depending on the parameter M_A (axial mass) to be determined from neutrino data. When the target nucleon is bound to the parent nucleus A, the non perturbative effects of strong interactions inside the target nucleus need to be taken into account. The description of these effects is carried out within dynamical models, necessarily involving assumptions and approximations that represent one of the main sources of systematic error. The resonance excitation channel from a theoretical point of view this is the most complex channel. The nucleon N is represented by a bound 3-quark system in its ground state, Δ and N^* are excited states decaying into pions. Each decay channel is the result of superposition and interference between allowed resonance amplitudes [2]. In reality N is bound to A, so that the treatment of the nuclear effects and FSI is very important for a good cross-section determination.

At low neutrino energy, ν-A reactions are very sensitive to the modeling of the dynamics determining the nuclear response. The nuclear initial state is "traditionally" described adopting the Relativistic Fermi Gas Model (RFG). This approach, that can be regarded as the simplest implementation of the independent particle model, rests on the assumption that nucleons behave like a degenerate gas of protons and neutrons bound with constant energy. Theoretical studies of electron-nucleus scattering have unambiguously shown that the RFG model, while being capable to describe the main qualitative features of the observed cross-sections, fails to provide a quantitative account of the effects of nucleon-nucleon correlations. The focus of my research will be replacing the oversimplified RFG model with a more adequate model, based on spectral functions (SF) obtained using a realistic description of nuclear dynamics, in the standard Genie [3] neutrino Monte Carlo generator. The need of more advanced nuclear models clearly emerged from the analysis of the last generation of inclusive, (e, e'), and semi-exclusive $(e, e'p)$ electron scattering experiments performed at Jefferson Lab. and, more recently, from experimental results reported by the MiniBooNE and KEK collaborations, indicating a suppression of the detected cross-section at $low - Q^2$ w.r.t. Monte Carlo simulations based on the RFG model. Various sophisticated models and calculations are in fact available for eN (in A) scattering. For example, Nuclear Spectral Functions $SF(E, p)$ [4] can be used to describe the eA cross-section in terms of $\sum \sigma(e, N) \times SF$ where (e,N) is the eN_{free} cross-section in impulse approximation and SF(E, p) is the probability of removing a nucleon of momentum p leaving the residual system with excitation energy E. Spectral functions, as calculated within the Nuclear Many Body Theory (NMBT) [5], include NN and $3N$ correlations and are successfully used in the analysis of A(e, e') data for light nuclei. Attempts to extend NMBT for ν-A reactions for light nuclei (for example ^{16}O(ν, l); $\nu = \nu_e$, ν_μ) yielded encouraging results [6] in accounting for the observed cross-section suppression at low-Q^2 from recent ν-data. Further exploitations of SF's in the ν-sector depend largely on the possibility of extending multi body calculations to heavy nuclei (Fe, Ar, Pb, . . .) and implementing the results into Monte Carlo simulations. A variety of Monte Carlo codes exists, e.g. NUANCE, NEUT, NEUGEN, NUX, GENIE, . . . , characterized by some common theoretical inputs, but also non-trivial differences. Genie has been the preferred choice in the last few years as the neutrino interaction Monte Carlo generator. Newly planned experiments will use it and older experiment are planning to provide an interface between their "proprietary code" and Genie. The experimental neutrino community realized together in the past few years the importance of having a unique Monte Carlo simulation for neutrino interactions. A further development of this project will consist in the inclusion in Genie of more complex reaction mechanisms, involving two-nucleon contributions to the nuclear weak current. [7].

Last but not least, the reason to have a refined neutrino Monte Carlo generator is the effects that nuclear effects have on neutrino energy reconstruction. This will be a particularly serious issue for global fits of world neutrino data, like for instance [8], since different experiments use different target nuclei, e.g. oxygen in T2K versus iron in MINOS; moreover, beam energies are very different as well, compounding the associated uncertainties. Each experiment will be affected by nuclear models and energy smearing due to misidentification of QE interactions in different way and this has to be accounted for in global fits. It is well known that first attempts at determining the mass hierarchy will have to rely on combined fits of NOvA, T2K and Daya Bay data and thus, this problem is not merely academic but will become a reality very soon.

References

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