Theoretical highlights on neutrino-nucleus interactions: current challenges

L. Alvarez-Ruso

Centro de Física Computacional, Departamento de Física, Universidade de Coimbra, Portugal

Abstract. The present theoretical status of neutrino interactions in the few-GeV region is reviewed. Quasielastic scattering, pion production and their importance for neutrino oscillation studies are discussed, making emphasis on the open questions that arise in the comparison with new experimental data.

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Recent years have witnessed an intense experimental and theoretical activity aimed at a better understanding of neutrino interactions with nucleons and nuclei. While the main motivation for these efforts is the demand from oscillation experiments in their quest for a precise determination of neutrino properties, the relevance of neutrino interactions with matter is more far-reaching. They are important for astrophysics, physics beyond the standard model, hadronic and nuclear physics.

In the few-GeV neutrino-energy region, where most oscillation experiments operate, the dominant reaction channel through which neutrinos reveal themselves (and their flavor) is charged-current quasielastic scattering (CCQE) $\nu_l\, n \to l^- \, p$. Oscillation probabilities depend on the neutrino energy, unknown for broad fluxes and usually obtained from the measured angle and energy of the outgoing lepton using two-body kinematics This determination is only exact for free neutrons and under the condition that inelastic events (mainly pion production ones) are identified and excluded. As detectors are composed of nuclei, the reconstructed energy is smeared due to the momentum distribution of the bound nucleons. Moreover, the E_ν determination could be wrong for a fraction of events that are not CCQE ones but look identical to them in the detector. Fake CCQE events can only be removed using a model dependent MC simulation. Therefore, a good insight into the dynamics of neutrino-nucleus (νA) collisions can be hardly underestimated.

The importance of weak pion production (πP) for oscillations studies is not limited to the contamination of CCQE samples. Neutral current (NC) π^0 production is a large background for ν_e appearance searches. When one of the two photons from a π^0 decay escapes detection, the π^0 cannot be distinguished from an electron born in a ν_e CC interaction. A precise determination of θ_{13} and the potential discovery of CP violation in the lepton sector requires that this background is reliably subtracted.

At the nucleon level, the weak interaction is defined by the current written in terms of form factors (FF) $F_{1,2,A,P}(Q^2)$. The axial FF F_A is usually parametrized in a dipole form in analogy to the electric FF of the proton at low Q^2. Once the coupling g_A is fixed from neutron β decay, the axial mass M_A, related to the axial mean square radius $\langle r_A^2 \rangle = 12/M_A^2$, remains the only unknown nucleon property. The value of M_A extracted from early CCQE measurements on deuterium targets is $M_A = 1.016 \pm 0.026$ GeV [1]. While one might be tempted to distrust this result based on experiments with low statistics and poorly know neutrino fluxes, there are good reasons to think that, at least at low Q^2, $M_A \sim 1$ GeV. Indeed, there is a low energy theorem that relates π electroproduction amplitudes to F_A at threshold and in the chiral limit. Using models to connect this theorem with data it has been found that $\tilde{M}_A = 1.069 \pm 0.016$ GeV [2]. Applying a hadronic correction that can be precisely calculated at low Q^2 using chiral perturbation theory [3], the resulting $M_A = 1.014 \pm 0.016$ GeV is even closer to the one from νd experiments.

The experience acquired in electron-nucleus scattering studies has been applied to the νA case. The simplest model in the QE region, present in most event generators used in neutrino experiments, is the relativistic global Fermi gas (RFG). It assumes the impulse approximation (IA) according to which the interaction takes place on single nucleons whose contributions are summed incoherently. The struck nucleons have momentum distributions characterized by a Fermi momentum p_F, and a constant binding energy ε_B. Outgoing nucleons cannot go into occupied states (Pauli blocking). Such a simple picture explains qualitatively inclusive QE electron scattering data but fails in the details. A better description requires a realistic treatment of nuclear dynamics. Interacting nucleons do not have a well defined dispersion relation but become broad states characterized by spectral functions (SF). In the relativistic mean field (RMF) model [4] the initial nucleons are treated as single-particle bound states whose wave functions are solutions of the Dirac equation with a σ-ω mean field potential. Another alternative to the RFG is the so called Local Fermi Gas (LFG) where the Fermi momentum depends on the coordinate through the nuclear density profile. A great advantage of LFG is that, owing to its simplicity, microscopic many-body effects such as SF [5, 6] and long range random phase approximation (RPA) correlations [7, 6, 8] are tractable in a realistic manner.

A common feature of all known calculations of the CCQE integrated cross section on ^{12}C applying the different theoretical techniques outlined above is that they underestimate recent MiniBooNE data (see Fig. 1).

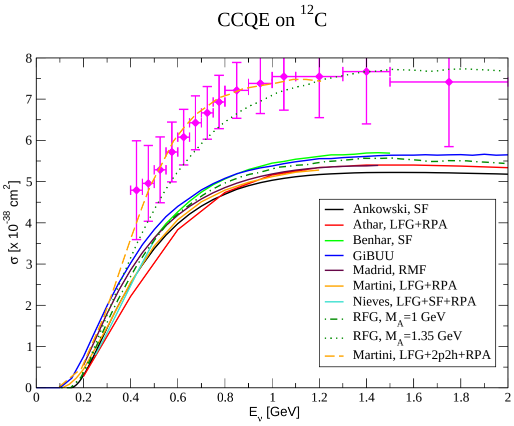

FIGURE 1. (color online) Summary of CCQE total cross sections. Solid lines denote the models from Refs [9], [10], [11], [12, 5], [4], [8] and [6] in this order, as reported in Ref. [13]. The dash-dotted and dotted lines are RFG calculations with $p_F = 220$ MeV, $\varepsilon_B = 34$ MeV and $M_A = 1$ and 1.35 GeV respectively. The dashed line is the result of Ref. [8] after adding the $2p-2h$ contributions. The data points are from MiniBooNE [14].

Several interpretations of this discrepancy are under debate. One strategy is to extract M_A from MiniBooNE data. In Ref. [14], a fit to the shape of the reconstructed Q^2 distribution with the RFG model yielded $M_A = 1.35 \pm 0.17$ GeV, which is much higher than the world average. The integrated cross section computed with the new value of M_A is consistent with the normalized data as can be seen in Fig. 1 (dotted line). A similar Q^2 fit but using a more elaborated distorted wave IA model, like the RMF sketched above obtained $M_A = 1.37$ GeV [15]. With a state-of-the-art SF, the best Q^2 fit and a good description of muon energy spectrum and angular distribution were found for an M_A as large as 1.6 GeV [16].

A third possibility has been put forward by Martini et al. [8]. They have studied inclusive νA scattering in a LFG using RPA and taking into account two-particle-two-hole ($2p-2h$) contributions, in particular some terms that are not part of the SF (see diagrams 2, 3, 3' in Fig. 1 of Ref. [8]). As shown in Fig. 1, with $1p-1h$ excitations alone, the prediction of this model is consistent with the rest but the $2p-2h$ component turns out to be substantially large and capable of explaining the size of the cross section measured by MiniBooNE. An interesting prediction of the model concerns the $\bar{\nu}$ CCQE reaction [17]: the different interaction pattern implies that, contrary to the neutrino case, $2p-2h$ excitations play a minor role. These suggestions should be further investigated by comparing the double-differential cross sections with data. The role of meson-exchange currents (MEC) and relativistic effects needs to be elucidated. Work in this direction has started with the calculation of vector MEC in the $2p-2h$ sector for the RFG [18].

The first step towards a good description of πP on nuclear targets is a realistic model of the elementary reaction (on nucleons). The most popular model for this process in neutrino interaction simulations was developed by Rein and Sehgal [19]. It assumes that πP on the nucleon is dominated by baryon resonance excitation, which is described a the relativistic quark model for resonances with invariant masses up to 2 GeV. It is worrying the poor description of electron scattering on the proton (see Fig. 2 of Ref. [20]) achieved due to the use of unrealistic vector FF. On the other side, the wealth of pion photo- and electro-production data available have been used to extract the electromagnetic transition helicity amplitudes [21, 22].

In contrast, there is almost no information about the axial part of the weak nucleon-to-resonance transition current. In the few-GeV region, weak πP is dominated by the excitation of the $\Delta(1232)$ resonance. At small Q^2, only the axial C_5^A FF is relevant and some effort has been devoted to its extraction from ANL and BNL bubble chamber data. In Ref. [23] $C_5^A(0)$ was extracted from the ratio of the inelastic $\nu_\mu d \to \mu^- \pi^+ p n$ and quasielastic $\nu_\mu d \to \mu^- p p$ Q^2 distributions measured at BNL. The result was $C_5^A(0) = 1.22 \pm 0.06$, compatible with the Goldberger-Treiman (GT) relation value of 1.2. Assuming a simple dipole parametrization Graczyk et al. [24] obtained $C_5^A(0) = 1.19 \pm 0.08$ and $M_{A\Delta} = 0.94 \pm 0.03$ GeV by directly fitting $d\sigma/dQ^2$ for $\nu_\mu d \to \mu^- \pi^+ p n$ ANL and BNL data taking into account normalization uncertainties. Both studies included deuteron effects but neglected nonresonant backgrounds. The nonresonant contribution close to threshold is fully determined by chiral symmetry [25]. Its inclusion required a 20 % reduction of the GT relation in order to describe ANL and BNL data [26].

When πP takes place inside the nucleus, the strong-interacting environment leaves a big imprint on the observables. The elementary amplitude is modified in the medium by the presence of the nuclear mean field and, most importantly, due to the modification of the $\Delta(1232)$ resonance. In addition, the produced pion can be absorbed or scatter with the nucleons with and without charge exchange. In the few-GeV region a large number of states can be excited so that the only feasible way of describing the exclusive final system is with a semiclassical treatment. The most common framework to deal with this is an intranuclear cascade but transport theory has also been used. In the NuWRO event generator [27] pions are produced via $\Delta(1232)$ excitation. Heavier resonances are only accounted for in the duality-inspired nonresonant background. Pion propagation is accomplished with an intranuclear cascade, with scattering probabilities determined by πN vacuum cross sections. Pion absorption is fixed according to pion nuclear absorption data. The model of Ahmad et al. [28] takes also into account the $\Delta(1232)$ in-medium change only in the production amplitude while the pion cascade uses vacuum cross sections. Finally, the Giessen Boltzmann-Uehling-Uhlenberg (GiBUU) model is a semiclassical transport model in coupled channels successfully applied to photo-, electro- and hadron-nucleus reactions and recently extended to νA collisions [12]. Not only the $\Delta(1232)$ but all the baryon resonances with masses up to 2 GeV can be weakly excited and are explicitly propagated. The medium modifications equally affect the production mechanism and secondary interactions.

MiniBooNE has measured the ratio $\sigma(\mathrm{CC}\pi^+)/\sigma(\mathrm{CCQE}-\mathrm{like})$ on CH_2 as a function of E_ν [29]. There is an uncertainty in the neutrino-energy reconstruction but, on the other side, this observable does not depend on the neutrino flux normalization. The three models described above have been employed to calculate this ratio: see Fig. 8 of Ref. [24], Fig. 1 of Ref. [30] and Fig. 2 of Ref. [31]. The comparison shows a good agreement at the lowest energies that gets progressively worse as the energy increase. Recall however that the three calculations have used $M_A \sim 1$ GeV for the CCQE cross section that enters the denominator, which is clearly insufficient to explain MiniBooNE CCQE data as shown in Fig. 1. Therefore it turns out all these models underestimate considerably MiniBooNE πP cross section.

New neutrino interaction data with high statistics, accompanied by a better understanding of the neutrino fluxes are becoming available from several experiments. The comparison with theory for some of the reaction channels that are relevant for oscillations studies reveals discrepancies that await explanation: fitting the new results with the available parameters is a dangerous strategy. The general tendency is that theory underestimates data but some flux-normalization independent quantities like the $\sigma(\mathrm{CC}\pi^+)/\sigma(\mathrm{CCQE}-\mathrm{like})$ ratio are also not well described. In order to achieve the precision goals in neutrino oscillation measurements it is crucial that the current theoretical developments are implemented in the event generators used in the experimental data analysis.

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