NEUTRINO INTERACTIONS: DOES NUCLEAR EFFECTS AND CROSS-SECTIONS UNDERSTANDING REALLY MATTER IN THE PRESENT/NEXT GENERATION ν-OSCILLATION EXPERIMENTS?*

Flavio Cavanna

Department of Physics and INFN, University of L'Aquila
Via Vetoio, 67010 L'Aquila, Italy

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The discovery of the neutrino non-standard properties (mass and mixing) refocused on various aspects of the neutrino standard properties, both from the theoretical and the experimental side. In particular, precise measurements and modeling of the ν-Nucleus Cross-Section in the *intermediate* energy range (~ 0.5–5 GeV), and related Nuclear Effects, are now considered as fundamental issues. In fact, these become necessary for a more robust control of the systematic uncertainties relevant in the forthcoming experimental effort aiming at precision measurements of the MNSP matrix elements. A critical review of the present knowledge motivated the origin and the activity of a wide community progressively formed around these issues. In this introductory review we provide with a qualitative summary of the achievements from the current activity in this field.

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1. The intermediate ν-energy range

The probability for ν-flavor transitions is governed by the quantum-mechanical phase difference developed by two ν-mass-eigenstates:

$$\Delta\phi_{jk} = (E_k - E_j)\ L \simeq \frac{\Delta m^2_{jk}}{2E_\nu}\, L\,. \tag{1}$$

The transition probability becomes relevant when (at least one) phase-difference is $\mathcal{O}(1)$. For the $(j,k=2,3)$ case in particular, once Δm^2_{23} is

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known ($\simeq 2.5\times10^{-3}$ eV^2) and L is defined, this determines the ideal neutrino energy E_ν for $\mathrm{P}(\nu_\mu \to \nu_\tau) = P_{\max}$

$$E_\nu \simeq 0.5\,\mathrm{GeV}\left[\frac{L}{250\ \mathrm{km}}\right] . \tag{2}$$

Therefore, neutrino energies of $\mathcal{O}(1\,\mathrm{GeV})$ represent a natural choice for LBL experiments (*e.g.* T2K, with $L = 295\,\mathrm{km}$) aiming at precision measurements of the oscillation mechanisms.

Such a defined range of interest thus lies *"intermediate"*, between the low-energy region of the Solar/Reactor/Beam-Dump/SN ν experiments and the high-energy interval exploited in the past in many short-baseline experiments (and in the current CNGS long-baseline experiments). As a consequence of that, the experimental data available in this range, necessary for a precise control of the ν cross-sections, are rather scarce and affected by large errors.

2. Theoretical issues

Accurate and precise knowledge of the ν cross-section, and of the related observables, plays an important role for the next generation of experiments. Various target nuclei, like C, O, Fe, Ar, Pb, ..., are normally (and presumably will be) employed to provide the detector mass. The ν-interaction on $p, n/q, \bar{q}$ in nuclei/nucleons is usually referred to according to a natural decompositions:

$$\begin{aligned}\sigma_{\mathrm{tot}} &= \sigma_{\mathrm{QEL}} \oplus \sigma_{\mathrm{RES}} \oplus \sigma_{\mathrm{DIS}} \\ &= \sigma_{0\pi} \quad \oplus \sigma_{1\pi} \quad \oplus \sigma_{n\pi} .\end{aligned} \tag{3}$$

In Fig. 1 a compilation of neutrino cross-section measurements is shown together with a Monte Carlo (MC) prediction calculated within the scheme of Eq. (3).

[σ_{QEL}] The first term in Eq. (3) refers to the quasi-elastic scattering:

$$\nu_l + n \to l^- + p\,, \tag{4}$$

characterized by low Q^2, $x_{\mathrm{Bj}} = 1$, $W = M_p$.

The dynamics can be described by a V–A current–current Lagrangian [1]. The hadronic current is usually defined through the nucleon weak Form Factors (FF): the vector FF's [$F_V^1(Q^2)$ and $F_V^2(Q^2)$], related to the El.M. FF under CVC-hypothesis, the axial [$F_{\mathrm{A}}(Q^2)$] and pseudoscalar [$F_{\mathrm{P}}(Q^2)$] FF's.

In particular, the vector FF's can be (are) determined from e-scattering experiments, while the axial FF is assumed to be in dipolar form depending on a free parameter M_{A} to be determined from ν-data fits. The pseudoscalar

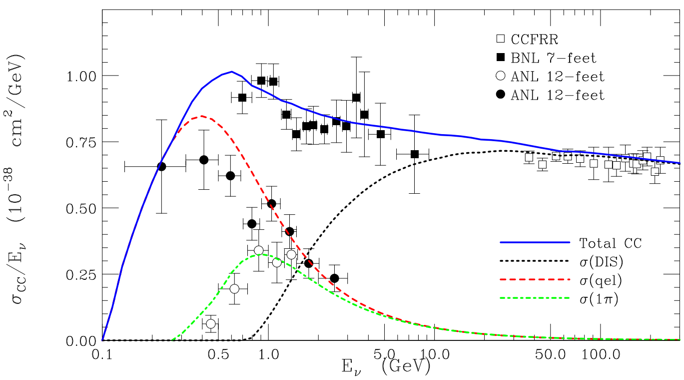

Fig. 1. Charged current ν_μ cross-section MC calculation [2] compared with data.

FF term in the cross-section turns out to be proportional to $(m_l/M_p)^2$, therefore, it is relevant only for $\nu_l = \nu_\tau$ cross-section formulae.

When the n-target nucleon (p for $\bar{\nu}$ interaction in (4)) is bound in the parent nucleus A the non-perturbative effects of strong interactions inside the target must be taken into account. In this case the absence of a well defined model makes the treatment of the nuclear effects a potential source of systematic uncertainty, as discussed below.

[σ_{RES}] The second term in Eq. (3) refers to the resonance excitation channel:

$$\nu_l + N \to l + \frac{\Delta}{N^*} \to l + \pi + N' \,, \tag{5}$$

characterized by low Q^2, large x_{Bj}, and W.

From the theoretical point of view this is the most complicated channel. According to the standard FKR model [3] the nucleon N is represented by a 3-quarks system bound by a harmonic potential in ground state. Δ and N^* correspond to excited states, decaying with π production. Each decay channel results from superposition and interference between allowed resonance amplitudes [4]. If N is bound in A, the treatment of the nuclear effects and of the Final State (re)Interactions (FSI) are even more crucial for a satisfactory cross-section determination. From the experimental point of view, this is the least precisely measured channel.

[σ_{DIS}] The third term in Eq. (3) refers to the (deep) inelastic interaction modes:

$$\nu_l + N \to l + X \,, \tag{6}$$

with $x_{\mathrm{Bj}} \in (0,1)$ and large Q^2.

Dynamics is well described by Standard Model propagator (massive $W^\pm$). The hadronic current is defined through the nucleon structure functions embedding the standard Parton Distribution Functions (PDF). Precise high-Q^2 DIS data are available from (e, e') experiments for F_1 and F_2 determination, and from ν–N experiments for F_3 fitting. F_4 and F_5 structure functions in the ν cross-section are proportional to (m_l^2/M_N), *i.e.* relevant only for $\nu_l = \nu_\tau$.

At DIS regimes nuclear effects have a limited impact. However, the (somehow crude) three-fold decomposition of Eq. (3) is not fully adequate to connect RES and low-Q^2 DIS regimes. Such a "twilight zone" provides some ground for new deeper theoretical investigations aiming at a more general description of the ν cross-sections.

The scenario depicted above, with a number of questions not fully resolved yet, has triggered a renovated interest [5] on the neutrino properties. This led to the current sparkling activity [6–8] in the theoretical field of the ν–A interaction, characterized by the overall goal of describing all three processes (QEL, RES, DIS) for both e and ν at all energies with an adequate modeling of the Nuclear Effects, and in the experimental field to proposals for new dedicated experiments exploiting the *intermediate* energy neutrino beams available in Japan and US.

Most of the relevant issues from this activity compose the program of the present Workshop where important upgraded results are also being presented.

2.1. Nuclear models and nuclear effects

At low ν-energy, comparable to nuclear excitations, ν–A reactions are very sensitive to the actual modeling of nuclear response (*e.g.* to NN correlations). Standard Nuclear Shell Models are effective in this energy range (up to $A \sim 60$).

When ν-energy increases, in the region of interest for super-nova neutrino detection, reactions on A target are sensitive to the giant resonance strength with transitions of the nucleus from ground state to the excited states in the continuum region above the nucleon emission threshold. Random Phase Approximation (RPA and CRPA) methods have been developed to describe the collective excitations of the nucleus ($1p$–$1h$ excitations of the correlated ground-state) [9].

At the *intermediate* ν-energies of our (main) interest, individual (quasi-free) nucleons are off scattered and the remaining $(A-1)$ nucleons can be treated as spectators (Eq. 4).

In this case nucleon form factors have to be suitably determined and parameterized (from e–N and ν–N experiments). New results have been recently presented (*e.g.* BBBA2005 FF-parametrization [10]) and other studies are under way *e.g.* about the determination of the strange content of the nucleon as probed by ν-scattering [11].

The nuclear initial state is "traditionally" described (within the ν-Community) adopting the Relativistic Fermi Gas (RFG) model [12]: this is the simplest approach for Monte Carlo implementation and is quite effective when additional features are added in (*e.g.* N–N correlations [13]).

In this case part of the Nuclear Effects are included: motion of the target N in the parent nucleus, Pauli blocking and nucleon binding effects, multi-N-body correlations (while shadowing and final state re-interactions in nuclear matter deserve subsequent treatment).

New inputs to reconsider more appropriate nuclear models came [5] from the $A(e,e')$ Community (*e.g.* from JLAB last generation exclusive e–A scattering experiments) and more recently [7] from some experimental ν results (MiniBooNE and KEK) indicating a detected cross-section suppression at low-Q^2 w.r.t. MC simulations adopting RFG model.

Various sophisticated models and calculations are in fact available for e–N (in A) scattering. As example, we mention the use of Nuclear Spectral Functions $\mathrm{SF}(E,p)$ [14] to describe the e–A cross-section in terms of $\sum \sigma(e,N)\times\mathrm{SF}$ where $\sigma(e,N)$ is the e–N_{free} cross-section in impulse approximation and $\mathrm{SF}(E,p)$ 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) [15], include N–N 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 (*e.g.* ${}^{16}\mathrm{O}(\nu,l); \nu=\nu_e,\nu_\mu$) yielded encouraging results [16] 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 largely depends on the possibility of extending MB calculations to heavy nuclei (Fe, Ar, Pb, ...) [17] and implementing the results into Monte Carlo simulations [18].

The other theoretical approaches, based on Relativistic Shell Models or Cascade Models in Local Density Approximation, result to be effective as well in describing the quasi-elastic regime [19]. In all cases the final state interactions are found to be large ($\geq 10\%$ effect) indicating the need of quantitative validation from new experiments.

At higher ν-energies, where resonance excitations with pion emission become the leading interaction channel (Eq. (5)), new improved Δ production models have been proposed [20]. In particular, based on recent JLAB electro-production data, a new set of (phenomenological) nucleon-resonance form factors have been obtained [21].

From a totally different approach we also mention the attempt to interpret RES scattering in terms of quark–parton model, or equivalently to extend high x PDF's at very low-Q^2. This is based on the quark–hadron duality features [22].

Challenging results in this twilight zone have been presented [23] with modified effective L.O. PDF's re-definition based on the use of a new scaling variable ($x_{\mathrm{Bj}} \rightarrow \xi_w$) to absorb target mass, higher twist, missing higher orders effects. Good agreement of the F_2 Structure Function with DIS $p, d(e, e')$ data has been obtained. Axial low-Q^2 PDFs are also available, but still need to compare to low-energy ν-data to get exact parameters.

Finally, moving to the upper edge of the *intermediate* ν-energies we step in the DIS regime (Eq. (6)). Here nuclear effects are still relevant in the structure functions, in particular coherent effects of interactions with a few nucleons (nuclear shadowing) have to be taken into account with appropriate corrections. Some recent studies have been presented in Ref. [24] and will be updated at this workshop [25].

3. Monte Carlo issues

In the ν-sector, in spite of the enormous experimental achievement of the last two decades, progress in the developments of comprehensive and widely available Monte Carlo simulations was rather limited for long time. Each experiment elaborated its own "proprietary" MC code, specific of their own running conditions, and practically without attempt to confront and test the validity of one's assumptions. A variety of MC codes existed, *e.g.* NUANCE, NEUT, NEUGEN, NUX, GENEVE, ..., characterized by some common theoretical inputs, but also non-trivial differences.

In the last few years source codes have been made available to the community allowing for in depth checks and comparisons among the adopted theoretical models.

In the QEL sector MC predictions have been studied and confronted with existing data. A good agreement among MC-generators has been found [26]. The evidence of a low-Q^2 problem in the differential cross-section w.r.t. new experimental data available from MiniBooNE [27] and K2K front detectors at KEK [28] demonstrates the importance of an appropriate model to describe the nuclear targets. All MC codes in fact adopt the Fermi Gas model and the discrepancy in reproducing the experimental data may be taken as a possible hint for a RFG (partial) inadequacy. In the RES sector different resonance models and methods for combining with DIS regime result in quite different MC kinematic distributions, the largest differences being in the low invariant mass region. Appropriate modeling of the nuclear effects and of final state interactions and propagation through the nuclear matter is the main limit in the present description of RES interaction [29]. On top of it, the comparison with experimental results is difficult due to the lack of data in this sector.

New inputs from the ongoing theoretical activity are, therefore, necessary and, even more important, new data, possibly from dedicated measurement(s), are eagerly awaited for MC tuning[1] in view of the second generation, high precision ν-oscillation experiments.

In the mean time, as initially suggested [5], the route toward a canonical Monte Carlo for neutrino interaction physics has been pursued. A Universal Object-Oriented/C++ Neutrino Monte Carlo Generator (GENIE), whose validity will extend to all neutrino types and nuclear targets in the energy range from few MeV to few hundred GeV, has been coded and proposed [30]. GENIE attempts to unify the Monte Carlo generation approaches used by a host of different, smaller procedural systems in a modern object-oriented software design [31].

4. Experimental issues

In the framework of the current search for ν-oscillation signals two neutrino beams (ν_μ from pion production off accelerated proton on target) are active in the *intermediate* ν-energy range: at KEK (Japan) and at FNAL-Booster (US) with mean energy of 1.3 GeV and 0.7 GeV, respectively, and low ν_e contamination.

On the FNAL-Booster beam the MiniBooNE experiment [32] is taking data since 2002 and collected hundreds thousand ν_μ-CC QEL events with a detector of 800 t of mineral oil. Precision measurements of QEL cross-section on C target have being published. An important output from the data analysis is the $d\sigma/dQ^2$ measurement providing indication of the already mentioned deficit in the low-Q^2 region w.r.t. MC expectation.

At KEK the LBL beam pointing to the SK detector (K2K experiment [33]) was monitored with a set of three near detectors: the 1 kT water Cherenkov detector, the SciFi detector (water target) and the SciBar fine grained scintillator calorimeter. From the SciFi detector a new measurement of the $M_{\rm A}$ parameter in the axial form factor for oxygen has been recently performed. From the SciBar detector (9.4 t of fiducial volume) preliminary data analysis shows a deficit of muons in the forward direction w.r.t. expectations, corresponding again to a low-Q^2 problem.

4.1. Future perspectives

The imminent completion of the NuMI beam-line at FNAL, with its extremely intense ν flux and with the availability of space at the MINOS near detector hall, offers an ideal venue for a high-statistics, high-resolution

[1] It is worth mentioning that a complete neutrino data resource has been recently made available: `http://durpdg.dur.ac.uk/hepdata/online/neutrino`. This provides with a definitive quantitative database of validated low-energy ν cross-section data with their associated statistical and systematic errors.

ν and $\bar{\nu}$-nucleon/nucleus scattering experiment. A proposal for a fully active and multi-target (C, Fe, Pb nuclei) detector, MINERνA (Main Injector Experiment ν–A) [34], has been approved in US.

The detector design is composed by a segmented plastic scintillator active volume (6.1 t) and at its upstream end by nuclear targets consisting of 1 t of Fe and Pb. With the (expected) excellent knowledge of the beam (at the level of 3% of systematics) the study of ν–A interactions in the *intermediate* energy range would be performed with unprecedented precision [35].

A proposal for another more specific experiment, FINeSSE [36], has been also submitted. The main task is to determine the spin carried by the *strange*-quark in the nucleon by measuring low-Q^2 ν–p elastic scattering events with an intermediate ν-energy beam (*e.g.* the FNAL-Booster beam).

Anything else from the experimental side?

Bubble-chambers have played a key role in probing the fundamental properties of ν-interactions. The Liquid Argon-Time Projection Chamber (LAr-TPC) technology developed within the ICARUS project [37] is considered the modern version of the bubble-chamber concept (the "electronic bubble-chamber"), with the additional features of a high resolution calorimetry and of a (virtually) unlimited active mass. The LAr-TPC technology, besides its application for detection of rare phenomena in underground environment (the ICARUS program at multi-kiloton mass scale), is ideal to also perform a wide variety of ν-physics studies in the *intermediate* energy range, thanks to the capability of single particle identification and detailed

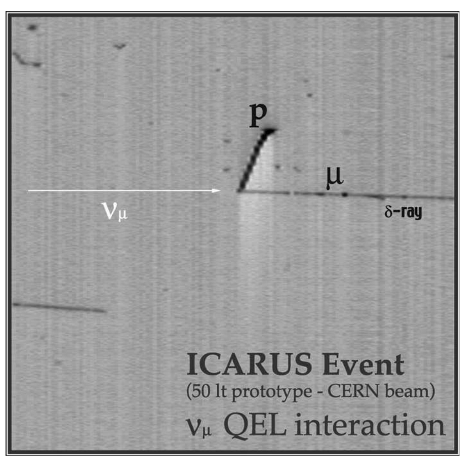

Fig. 2. ICARUS Event: QEL interaction $\nu_\mu + n(\mathrm{Ar}) \rightarrow \mu + p$ from the 50lt LAr prototype exposed to the CERN WANF beam [42]. The mip-like muon track, with visible δ-ray activity, escapes the LAr volume, the dense ionizing (darker) p-recoil track is fully contained.

reconstruction of exclusive topologies. As examples we mention the e-to-π^0 separation [38], useful for NC *versus* CC study, and the detection capability for the recoiling proton in QEL and RES interactions possibly down to the very low threshold of about 30 MeV of kinetic energy, necessary for a precise reconstruction of the initial state, *e.g.* see Fig. 2 where an ICARUS image of a QEL ν_μ-event is shown.

Possibilities of using a "small" — $\mathcal{O}(100\ \mathrm{t})$ — LAr detectors for dedicated cross-sections measurements in available, present [39] or future [40] ν-beams have been investigated and are currently being presented [41] and formally proposed.

5. Conclusions

Neutrino cross-sections measurement, theory and Monte Carlo of second generation are now recognized as a well established, necessary step toward the forthcoming second generation of oscillation experiments.

Neutrino beams in the *intermediate* energy range are (and others soon will be) available in US and Japan, providing an unprecedented richness of experimental opportunities for the next decade of activity.

First high statistics results on the standard ν properties from running (oscillation) experiments start to come out and to impose constraints on the theoretical models presently adopted.

From the theoretical ground a renewed effort is under way in elucidating the understanding of the neutrino interaction mechanisms with the nuclear matter. In parallel with both experimental and theoretical progress an important activity aiming at defining a universal Monte Carlo description of neutrino interactions in the intermediate energy range is presently under way and started already to give results in the comparison of the most used MC codes. Proposals for new dedicated experiments are (and other soon will be) approved/submitted. The realization of these experiments employing state-of-art technologies and profiting of the precise knowledge and intensity of the new neutrino beams is considered as necessary for the definitive assessment of the standard neutrino properties in view of the forthcoming next generation of ν-oscillation experiments.

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