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THE LIQUID ARGON TPC TECHNOLOGY FOR PRECISE (QUASI-ELASTIC) NEUTRINO CROSS-SECTIONS RECONSTRUCTION*

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Precise measurements and modeling of the ν-nucleus cross-section in the *intermediate* energy range (~ 0.5–$5\,\mathrm{GeV}$), and related nuclear effects, are today considered as fundamental issues for a robust control of the systematic uncertainties in the forthcoming experimental effort aiming at precision measurements of the MNSP matrix elements. The LAr TPC technology is ideal to perform a wide variety of ν-physics studies in the *intermediate* energy range, thanks to the capability of single particle identification and detailed reconstruction of exclusive topologies. The ArgoNeuT detector, recently put into operation on the low energy NuMI beam line at FNAL, may provide with first data and precision measurements of quasi-elastic ν–Ar cross-section.

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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 ($\simeq 2.5 \times 10^{-3}$ 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, neutrinos in the "few-GeV" energy range represent a natural choice for long baseline (LBL) experiments (*e.g.* T2K, NOνA with $L = 250, 750\,\mathrm{km}$) aiming at precision measurements of the oscillation mechanisms.

At these *"intermediate"* energies the charged-current (CC) cross-section for ν-interaction on $p, n/q, \bar{q}$ in nuclei/nucleons is usually referred to according to a natural decompositions:

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

where

- the first term in Eq. (3) refers to the Quasi-Elastic Scattering (QE):

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

  characterized by low Q^2, $x_{\mathrm{Bj}} = 1$, $W = M_p$. The dynamics can be described by a V–A current–current Lagrangian. 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 usually assumed to be in dipolar form and depending on a free parameter M_{A}, the axial mass to be determined from ν-data fits. The axial mass describes the nucleon structure and the axial FF determines a large fraction of the total QE cross-section. When the n-target nucleon [p for $\bar{\nu}$ interaction in (4)] is bound in the parent nucleus A, the Relativistic Fermi Gas model (RFG) is usually adopted to describe the nuclear initial state. Final state particles (hadrons) produced at the primary neutrino collision undergo non-perturbative effects (FSI) of strong interactions inside the target nucleus. In this case the absence of well defined models makes the treatment of these *"nuclear effects"* the main potential source of systematic uncertainty.

- the second term in Eq. (3) refers to the Resonance Excitation channel (RES)

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

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 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. 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.

- the third term in Eq. (3) refers to the (Deep) Inelastic Interaction modes (DIS)
$$\nu_l + N \to l + X \,, \tag{6}$$
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.

The available cross-section measurements (in particular for the QE and RES channels) from *"1st generation"* experiments (1964–1990) at ANL, BNL, FNAL, CERN and IHEP are affected by large errors, mainly due to low statistics, background contamination and to a limited control of the incoming neutrino flux amplitude and profile.

The lack of a well established knowledge of the neutrino cross-section in the "few GeV region" (with up to 40% difference among the reported results) is considered today one of main sources of systematics in view of the next generation ν-oscillation measurements. This triggered in the last few years renewed interest [1] and intense activity [2–6] on precise measurements and modeling of the ν-nucleus cross-section in this *intermediate* energy range (~ 0.5–$5\,\mathrm{GeV}$), and related nuclear effects.

2. Experimental issues

In the framework of the current search for ν-oscillation signals two neutrino beams were/are active in the *intermediate* ν-energy range: at KEK (Japan) and at FNAL–Booster (USA) with mean energy of $1.3\,\mathrm{GeV}$ and $0.7\,\mathrm{GeV}$, respectively, and low ν_e contamination.

On the FNAL–Booster beam the MiniBooNE experiment [7] collected large statistics of ν_μ-CC QE events with a detector of 800 t of Mineral Oil. Measurements of QE cross-section on C target have been published. At KEK the LBL beam pointing to the SK detector (K2K experiment [8]) 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_{A} parameter in the axial form factor for oxygen has been performed. However, the situation remains unclear mainly due to (still) large errors associated to their results.

The SciFi detector was successively transported to FNAL and positioned along the FNAL–Booster beam line (SciBooNE experiment [9]). A dedicated run allowed the collection of a new set of data for ν cross-section measurements in the *intermediate* energy range. New important results are being published.

Finally, it is worth mentioning a recent study [10] by the NOMAD Collaboration on data collected from the exposure (1995–1998) of the active low-Z target of the NOMAD experiment to the CERN wide band beam at substantially higher neutrino energies (average 26 GeV). The high statistics and the normalization to the well-known total DIS cross-section allowed the first precise QE cross-section measurement in the high energy range ($\sim$ from 5 GeV to 80 GeV).

Complete collection and comprehensive review of all available data on QE cross-section and M_{A} measurements is also given in [10].

2.1. Future perspectives

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 high-statistics, high-resolution ν and $\bar{\nu}$–nucleon/nucleus scattering experiments. A fully active and multi-target ($A =$ C, Fe, Pb nuclei) detector, MINERνA (Main Injector Experiment ν–A) [11], is presently under assembly. Once operational, the study of ν–A interactions in the *intermediate* energy range would be then performed with unprecedented precision for the most commonly used nuclear targets.

Argon target ($A = 40$) is also of high interest for possible application with next generation ν-oscillation experiments. In fact, the Liquid Argon-Time Projection Chamber (LAr TPC) technology developed within the ICARUS project [12], considered the modern version of the bubble-chamber concept, combines the imaging capability with the additional features of a high resolution calorimetry and of a (virtually) unlimited active mass. Moreover, thanks to the single particle identification and detailed reconstruction of exclusive topologies (*e.g.* with e-to-π^0 separation, useful for NC *versus* CC study, and with the detection of the recoiling proton in QE and RES interactions possibly down to the very low threshold of about $T_p \simeq 20$–$30\,\mathrm{MeV}$ of kinetic energy), can provide precise reconstruction of the initial state. Therefore, it definitively represents an ideal tool for the study of ν cross-sections, vertex reconstruction and nuclear effects (especially in the "few GeV range").

Possibilities of using LAr TPC detectors for dedicated cross-sections measurements in available ν-beams have been first investigated in 2001 (F.C. Palamara, O. Palamara [1]) and further discussed in the following years up to the approval (2007) of a small test experiment (ArgoNeuT) to be positioned on the NuMI beam-line at FNAL.

In the next section, a brief overview of the results from the exposure of a "50 lt" LAr TPC prototype (ICARUS) to a *high-energy* ν-beam at CERN in 1997 will be given; in the last section the perspectives from the exposure of the 175 lt ArgoNeuT detector to the "low-energy" NuMI beam (just started) at FNAL will be presented.

2.2. The "50 lt" LAr TPC at WANF

The first exposure of a LAr TPC to neutrinos (ICARUS R&D program) was performed in 1997–1998 at the CERN West Area Neutrino Facility (WANF), where the high-energy wide band beam was available for the CHORUS and NOMAD experiments. The data have been collected with a small LAr chamber located between them. The capability to identify and reconstruct low multiplicity neutrino interactions was clearly demonstrated with this test and also a first indication about the ν–Ar QE cross-section was extracted from data analysis.

The technical description of the detector is given in [13]. The modest size of the LAr TPC fiducial volume ($32 \times 32 \times 47\,\mathrm{cm}^3$ corresponding to about $\sim$50 lt), coupled with the high energy of the WANF ν beam (mean value 28 GeV), made necessary the use of a muon spectrometer downstream the TPC. To this purpose, a coincidence with the NOMAD DAQ was set up to profit of the detectors located into the NOMAD magnetic dipole as a magnetic spectrometer. The development of the event reconstruction procedures applied to the collected data allowed to extract the physical information from the TPC wire output signals, *i.e.* the energy deposited by the different particles and the point where such a deposition has occurred, up to build a complete 3D and calorimetric picture of the event (see Fig. 1 for an example of QE event 3D reconstruction). This was the first time that interactions of (multi GeV) accelerator neutrinos occurring in a LAr TPC were fully reconstructed.

Over the whole data taking period around 10000 triggers showed a vertex in the LAr TPC fiducial volume and were identified as ν_μ CC candidates. A selected QE "$\mathcal{G}$*olden sample*" has been extracted by application of tight

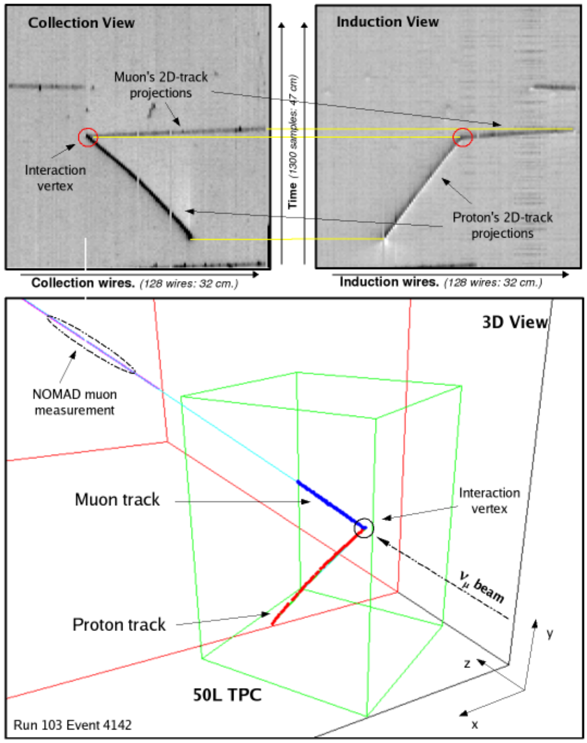

Fig. 1. Example of the 3D reconstruction of a low-multiplicity (QE) ν_μ CC event. The raw image from the two TPC wire planes (top): Hits and 2D track projections have been identified. Three dimensional view of the reconstructed event (bottom).

cuts. This set consists of events with an identified, fully contained proton and one muon whose direction extrapolated from NOMAD matches the outgoing track in the TPC. The study of proton identification and momentum measurement is particularly important: a negligible $\pi^\pm/p$ misidentification probability and a precise interaction vertex reconstruction were achieved with a (conservative) threshold of $T_p \geq 40\,\mathrm{MeV}$. Indeed, the size of the range of the fully contained protons collected in the QE selected sample offered the opportunity to precisely evaluate the energy loss pattern in the active LAr medium. The "$\mathcal{G}$*olden sample*" ($N_{\mathcal{G}} = 86$) contains pure QE interactions plus an intrinsic background dominated by RES and DIS production followed by pion absorption in the nucleus (or escaping undetected). Geometrical detector acceptance, background subtraction and QE selection efficiencies have been evaluated using Monte Carlo simulation and the numerical results rely on the choice of the input MC parameters. Beam intensity and exposure time were known parameters as well as the mean neutrino energy, estimated to be 28 GeV (with an RMS of 18 GeV). All numerical values are reported in [13] and the QE ν_μ–Ar cross-section at the mean beam energy amounts to $\sigma_{\mathrm{QE}} = (0.90 \pm 0.10(\mathrm{stat})) \times 10^{-38}$ cm^2. This value nicely agrees with the result obtained by NOMAD [10] (same ν-beam).

The estimated total systematic error, evaluated in a separate (yet unpublished) report, is about 20%. The dominant contribution is from the QE selection efficiency. This is affected by nuclear effects, which modify the topology and kinematics of the final state. Due to the large uncertainties in the modeling of nuclear effects inside the Monte Carlo, the systematic error on the cross-section due to the fraction of $\mathcal{G}olden$ events inside the QE sample amounts to about 16%.

2.3. The "ArgoNeuT" LAr TPC at FNAL

ArgoNeuT is a joint NSF/DOE R&D project (T962) at Fermilab [14] to expose a small-scale LArTPC to the NuMI neutrino/antineutrino beam. In the low energy configuration the NuMI facility produces a nearly pure ν_μ ($\bar{\nu}_\mu$) beam with energies in the 0.5–5 GeV range (peaking at ~ 3 GeV). ArgoNeuT with its 500 lt of liquid Argon (175 lt fiducial) it is located in the MINOS Near Detector hall, just upstream MINOS-ND, using the MINOS detector as a range stack to measure uncontained long-track muons from muon neutrino interactions in the TPC. The ArgoNeuT TPC dimensions are approximately $0.5m \times 0.5$ m $\times$ 1m and it is housed in a cylindrical vacuum insulated cryostat. The TPC has 480 active wires in two planes, with individual electronic read-out (analog preamp stage and waveform fast digital conversion). The planes are oriented at $\pm 30°$ to the vertical. Wire planes separation and wire-to-wire pitch are of 4mm. Signal feed-throughs and support equipments are mounted on a flange on the top of the vessel. An external trigger system composed by scintillator pads in front and behind the cryostat along the beam line completes the experimental layout. Commissioning of the detector and of the cryogenic system in a dedicated experimental facility on surface took place at FNAL in summer 2008 with first cosmic muon events recoding. The experimental set-up was then moved to the MINOS-ND Hall about 100 m underground. After remounting and LAr filling, data-taking started in May 2009 and is presently under way (up to the end the scheduled NuMI run period in neutrino mode, June '09). From September 2009 the beam in antineutrino mode will be restarted and later in 2010 ArgoNeuT will be exposed for another long neutrino beam run. Data from the present short period of exposure were useful for tuning of the detector performance and development of automated event reconstruction software. In Fig. 2 examples of 2D images of neutrino events collected are shown.

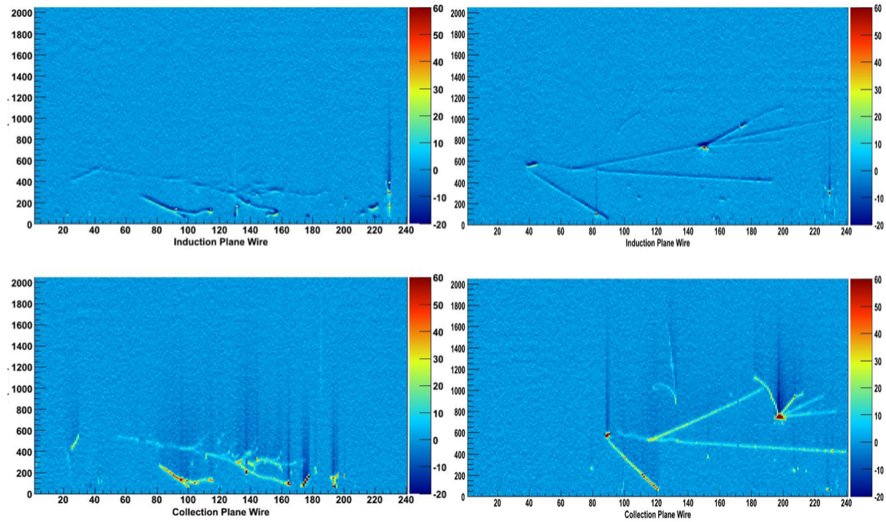

Fig. 2. Example of 2D (raw) images of ν_μ events from the two LAr TPC wire planes, collected with ArgoNeuT during the first neutrino run at NuMI-FNAL (May–June, 2009).

Main goal of the ArgoNeuT experiment is to directly measure ν_μ (and $\bar{\nu}_\mu$) cross-section on Argon in the "few GeV" range, with particular interest on the CC QE contribution and the related nuclear effects. The extraction of the $M_{\rm A}$ parameter, never measured with Ar target, is also of interest. A preliminary Monte Carlo simulation has demonstrated the feasibility of a precise CC QE cross-section measurement with ArgoNeuT. Under a standard assumption of 8×10^{17} PoT/day delivered at NuMI-FNAL, the expected number of ν_μ CC events/day has been evaluated as $N_{\rm tot} = 117$ from the three main channels of Eq. (3) ($N_{\rm QE} = 19$, $N_{\rm RES} = 15$, $N_{\rm DIS} = 83$ evts/day). These represent the number of events per day where the interaction vertex is found inside the boundaries of the LAr TPC active volume. From the MC simulation of QE events, proton tracks are fully contained in the LAr sensitive volume in a fraction of 54% of the total and 86% of muons enter the MINOS NEAR Detector (and the momentum is measured). The incident neutrino energy E_ν can then be rather precisely reconstructed for each QE event from the measured final state muon and proton 4-momentum vectors, assuming the target neutron with off-shell mass and Fermi momentum from RFG model. Considering as a reference "run period" with the ArgoNeuT detector the time needed to collect 1.4×10^{20} PoT (180 days of live-time), the QE cross-section can be reconstructed in the energy range between 1 and 4 GeV with relative statistical error in bins of 0.5 GeV reduced to the level of $\leq 5\%$, as reported in Fig. 3.

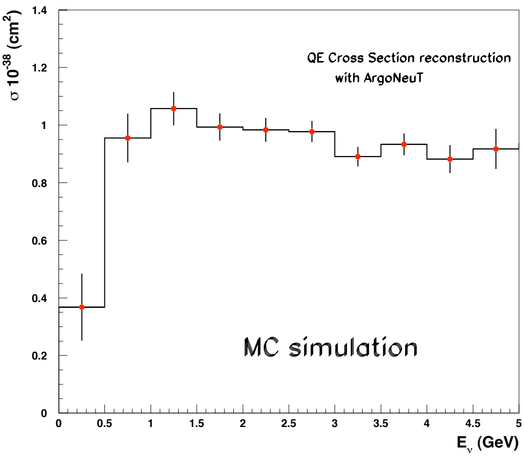

Fig. 3. MC simulation of QE cross-section reconstruction with ArgoNeuT.

The total cross-section $\sigma_{\rm QE}$ is extremely sensitive to $M_{\rm A}$ variation (it scales almost linearly with $M_{\rm A}$). The wide spread in the fitted values of $M_{\rm A}$ ($\sim$ from 0.7 to 1.3 GeV) from the presently available experimental data on QE cross-section remains very topical. Counting of the total number of QE interactions in the ArgoNeuT detector may provide itself a mean to extract a new $M_{\rm A}$ value (for the first time determined from Argon target). The accuracy of this result strongly depends on how well the NuMI beam characteristics are known. On the other hand, the high identification capability of QE events [for the two-tracks (μ, p) sample and for the single-track sample ($\mu \oplus$ possibly associated vertex activity from de-excitation mechanisms of the intranuclear cascade)] may lead to suppression of the other main source of systematic error (FSI effects).

3. Conclusions

Neutrino cross-sections measurement of second generation is now recognized as a well established, necessary step toward the forthcoming second generation of oscillation experiments.

Neutrino beams in the *intermediate* energy range are available in USA and Japan, providing an unprecedented richness of experimental opportunities.

The realization of experiments employing state-of-art technologies is considered as necessary for the definitive assessment of the standard neutrino properties.

The LAr TPC represents an ideal tool for the study of ν cross-sections, vertex reconstruction and nuclear effects in the "few GeV range". The exposure of the ICARUS "50 lt" LAr TPC prototype to the *high-energy* ν-beam at CERN in 1997 clearly demonstrated the capability to identify and reconstruct low multiplicity neutrino interactions and also provided a first indication about the ν–Ar QE cross-section.

The perspectives from the exposure to the low energy NuMI beam at FNAL of ArgoNeuT, a new LAr TPC detector recently commissioned, are very appealing: the QE cross-section can be reconstructed in the *intermediate* energy range between 1 and 4 GeV with relative statistical error in bins of 0.5 GeV reduced to the level of $\leq 5\%$.

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