Neutrino Interactions on Ar target

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Abstract. The forthcoming experimental effort aiming at precision measurements of the MNSP matrix elements requires a robust control of the systematic uncertainties. A major contribution is presently represented by the large (still persisting) uncertainty associated to the neutrino cross sections. Therefore, precise measurements and modeling of the $\nu$-Nucleus Cross-Section and related Nuclear Effects in the intermediate energy range ($\sim 0.5$-5 GeV) are today considered as relevant issues.

The LAr-TPC technology is ideal to perform a wide variety of $\nu$-physics studies, thanks to the capability of single particle identification and detailed reconstruction of exclusive topologies, as demonstrated within the ICARUS R&D program.

The ArgoNeuT detector, a 175 lt active LAr-TPC put into operation on the LE NuMI $\nu$-beam line at FNAL in 2009-10, is providing with first data for precision measurements of (quasi-elastic) $\nu$-Ar Cross-Section in the intermediate energy range.

1. The Intermediate $\nu$-Energy range

The field of neutrino oscillations, being these conclusively observed by solar, reactor, atmospheric, and accelerator-based neutrino oscillation experiments of first generation, has moved to an era where experiments will seek to precisely measure the oscillation parameters and search for the existence of a subdominant mode of oscillation. In the standard parameterization, within the three neutrinos scheme, neutrino oscillations are described by the MNSP mixing matrix through the squared differences of the neutrino mass eigenvalues, three mixing angles and one CP-violating phase.

The observed oscillation of electron neutrinos and anti-neutrinos from the sun and nuclear reactors, respectively, are primarily driven by the "$i,j = 1,2$" sector while the "2,3" sector describes the oscillation of $\nu_\mu$ to other neutrino flavor observed in atmospheric and accelerator experiments. This leads to subdominant oscillations that may manifest itself experimentally as a tiny appearance of $\nu_e$ in beam of $\nu_\mu$ detectable by accelerator experiments if $\theta_{13} > 0$. If the irreducible phase $\delta$ is also non-zero, neutrinos will also exhibit CP violation in which neutrino oscillations and the corresponding antineutrino oscillations will have different oscillation probabilities.

In present and future stages, accelerator-based experiments will perform high-sensitivity search for the $\nu_\mu \rightarrow \nu_e$ oscillation associated with non-zero $\theta_{13}$ using long-baseline neutrino beams in the "few-GeV" energy range (this lies "intermediate" between the "low" energy domain of solar and reactor neutrinos and the "high" energy range of accelerator neutrinos, e.g. appropriate for $\nu_\tau$ appearance).
The ability to carry out this ambitious program depends heavily on the full understanding of the neutrino ("standard") interaction mechanisms with the nuclear matter (A nucleus chosen as target in the detector).

An accurate determination of the experimental sensitivity is in fact a key element for a correct design of the experiment and this in turn should be based on the accurate, a priori knowledge of the beam flux and $\nu$-$\Lambda$ cross-section for all neutrino types (rather than on effective models, usually - so far - "tuned" up to match data to take care of the differences in fluxes (& detectors) at Near/Far locations).

2. $\nu$ Cross Section at the intermediate energies

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

$$\sigma_{tot} = \sigma_{QE} \oplus \sigma_{RES} \oplus \sigma_{DIS} = \sigma_{0\pi} \oplus \sigma_{1\pi} \oplus \sigma_{n\pi}$$ (1)

where:

- the first term in Eq.(1) refers to the Quasi-Elastic Scattering (QE):
  $$\nu_l + n \rightarrow l^- + p$$ (2)

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

  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 [$F_1^V(Q^2)$ and $F_2^V(Q^2)$], related to the El.M. $FF$ under CVC-hypothesis, the Axial [$F_A(Q^2)$] and PseudoScalar [$F_P(Q^2)$] $FF$'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 $\nu$-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 (2)] 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.(1) refers to the Resonance Excitation channel (RES):
  $$\nu_l + N \rightarrow l + \Delta/N^* \rightarrow l + \pi + N'$$ (3)

  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. $\Delta$ and $N^*$ correspond to excited states, decaying with $\pi$ production. Each decay channel results from superposition and interference between allowed resonance amplitudes.

  When $N$ 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.(1) refers to the (Deep) Inelastic Interaction modes (DIS):

\[ \nu_l + N \rightarrow l + X \]  \hspace{1cm} \text{(4)}

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

The interaction 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 \( \nu-N \) experiments for \( F_3 \) fitting. \( F_4 \) and \( F_5 \) Structure Functions in the \( \nu \) Cross-Section are proportional to \( (m_l^2/M_N) \), i.e. relevant only for \( \nu_l = \nu_\tau \).

Nuclear Effects have a limited impact at the DIS regimes.

The available Cross-Section measurements (in particular for the QE and RES channels) from ”1st generation” experiments (’64-’80) at ANL, BNL, FNAL, CERN and IHEP were affected by large errors, mainly due to low statistics, background contamination and to a limited control of the incoming neutrino flux amplitude and profile (with \( \sim 40\% \) spread across experiments).

This triggered a renewed interest (NuInt Workshop series) [1] and intense activity [2],[3],[4],[5],[6],[7] on precise measurements and modeling of the \( \nu \)-Nucleus Cross-Section in this intermediate energy range (\( \sim 0.5-5 \) GeV), and related Nuclear Effects.

Two neutrino beams were/are active in the intermediate \( \nu \)-energy range: at KEK (Japan) and at FNAL-Booster (US) with mean energy of 1.3 GeV and 0.7 GeV respectively and low \( \nu_e \) contamination. In the framework of the search for \( \nu \)-oscillation signals, cross-section measurements of ”2nd generation” (’90-’00) have been performed with the FNAL-Booster beam and at KEK on the LBL beam pointing to the SK detector.

The MiniBooNE experiment at FNAL [8] collected large statistics of \( \nu_\mu \)-CC QE events with a detector of 800 t of Mineral Oil. Measurements of QE Cross-Section on C target have been reported [6].

At KEK the beam pointing to the SK detector (K2K experiment [9]) 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 Pb-scintillator calorimeter. From the SciFi detector a new

![Figure 1. Quasi-Elastic \( \nu_\mu \) CC cross section data from ”2nd generation” experiments: MiniBooNE, SciBooNE, NOMAD (T. Katori in [6]). A single point (light blue star) corresponding to the data from the ICARUS 50 lt LAr-TPC prototype has been added as obtained from [14].](image-url)
measurement of the $M_A$ parameter in the Axial Form Factor for Oxygen has been performed. The SciFi detector was successively transported to FNAL and positioned along the FNAL-Booster beam line (SciBooNE experiment [10]). A dedicated run allowed the collection of a new set of data for $\nu$ Cross-Section measurements [6].

Finally, a study [11] by the NOMAD Collaboration has recently been published on data collected from the exposure (1995-98) of the active low-Z target of the NOMAD experiment to the CERN wide band beam, though 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).

Though the precision of the individual measurements improved substantially compared to the data from the 1st generation, a large ($\sim$ 30%) discrepancy still persists between measurements at low and high energies, as shown in Fig.1 for the quasi-elastic CC cross section.

The need for more accurate measurements thus remains an open issue in view of the next generation $\nu$-oscillation experiments.

3. Perspectives from the 3rd Generation of $\nu$ Cross Section measurements

The NuMI beam-line at FNAL, with its extremely intense $\nu$ flux and with the availability of space at the MINOS near detector hall, offers an ideal venue for high-statistics, high-resolution $\nu$ and $\bar{\nu}$-nucleon/nucleus scattering experiments.

The MINOS Near Detector itself, operational since 2005, has already recorded many million neutrino interactions on Fe nuclei at neutrino energies around 3 GeV (peak of the LE NuMI flux). Characteristics of the QE CC process have been reported [6].

A fully active and multi-target ($A = C, \text{Fe, Pb nuclei}$) detector, MINER$\nu$A (Main Injector Experiment $\nu$-A) [12], is presently under assembly (almost complete). Once operational, the study of $\nu$-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 $\nu$-oscillation experiments.

The liquid Argon-Time Projection Chamber (LAr-TPC) technology developed within the ICARUS project [13], 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-$\pi^0$ separation, useful for NC vs CC study, and with the detection of the recoiling proton in QE and RES interactions possibly down to the very low threshold of about $T_p \simeq 20-30$ MeV of kinetic energy), LAr-TPC detector(s) can provide most precise reconstruction of neutrino events.

Direct measurement of $\nu$-Ar interaction cross section at the intermediate energies haven’t been performed so far. LAr-TPC detectors, even at modest mass scale, definitively represents an ideal tool for the study of $\nu$ Cross-Sections, vertex reconstruction and nuclear effects (especially in the "few GeV range"). Final State hadrons from $\nu$-interactions may indeed re-interact inside the (parent) nuclear matter, before propagation in the detector volume, with emission of additional particles (neutrons, protons, $\pi$’s, $\gamma$’s, $\alpha$’s,...). These products are usually neglected because not detectable, unless a high quality imaging detector is in use or, if detected, may lead to mis-identification of the final state topology, unless robust PID criteria are at hand.

The capability to identify and reconstruct neutrino interactions in LAr-TPC’s was clearly demonstrated by a "50 lt" prototype (ICARUS) with a $\nu$ test beam at CERN in the late ’90’s and also a first indication about the $\nu$-Ar QE Cross-Section was extracted from the data analysis.

Possibilities of using LAr-TPC detectors for dedicated Cross-Sections measurements in available $\nu$-beams have been first investigated in 2001 (F.Cavanna and O. Palamara [1]) and
further discussed in the following years. In 2007 a small experiment (ArgoNeuT, B. Fleming et al. [15]) to be positioned on the NuMI beam-line at FNAL has been finally approved, as a first step in the vast experimental program of $\nu$-physics with LAr-TPC’s in the US. The use for Cross-Sections measurements of a $\sim$ 100 t LAr-TPC detector at the proposed intermediate (2 km) station on the T2K beam line as been also envisaged (A. Ereditato and A. Rubbia in [3] and A. Meregaglia and A. Rubbia in [7]).

In the next sections, a brief overview of the results from the exposure of the ICARUS ”50 lt” LAr-TPC prototype to the high-energy $\nu$-beam at CERN will be given as well as the perspectives and preliminary results from the exposure of the 175 lt ArgoNeuT detector to the “low-energy” (LE) NuMI beam at FNAL.

3.1. The ICARUS ”50 lt” LAr-TPC at CERN

The first exposure of a LAr-TPC to neutrinos (ICARUS-Milano U. R&D program) was performed in 1997-98 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 technical description of the detector is given in [14]. The modest size of the LAr TPC fiducial volume ($32 \times 32 \times 47$ cm$^3$ corresponding to about $\sim$50 lt), coupled with the high energy of the WANF $\nu$ 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 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. 2 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 these were identified as $\nu_\mu$ CC candidates. A selected QE “Golden sample” has been extracted by application of tight 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 the proton identification and the momentum measurement is particularly important: a negligible $\pi^+/p$ misidentification probability and a precise interaction vertex reconstruction were achieved with a (conservative) threshold of $T_p \geq 40$ 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 “Golden sample” ($N_G = 86$) contains pure QE interactions plus an intrinsic background dominated by RES and DIS production followed by pion absorption in the nucleus (or escaping undetected).

The geometrical detector acceptance, the background subtraction and the QE selection efficiencies have been evaluated using Monte-Carlo simulation and the numerical results rely on the choice of the input MC parameters. The beam intensity and the exposure time were known parameters as well as the mean neutrino energy, estimated to be 28 GeV with an RMS of 18 GeV (all the numerical values are reported in [14]).

The QE $\nu_\mu$-Ar Cross-Section at the mean beam energy amounts to $\sigma_{QE} = (0.90 \pm 0.10(stat)) \times 10^{-38}$ cm$^2$. This value nicely agrees with the result obtained by NOMAD [11] (same $\nu$-beam) as shown in Fig.1.

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 Golden events inside the QE sample amounts to about 16%.

3.2. The "ArgoNeuT" LAr-TPC at FNAL

ArgoNeuT is a joint NSF/DOE R&D project (T962) at Fermilab [15] to expose a small-scale LArTPC to the NuMI neutrino/antineutrino beam. In the LE configuration the NuMI facility produces a nearly pure $\nu_\mu$ ($\bar{\nu}_\mu$) beam with energies in the 0.5-5 GeV range (peaking at $\sim$3 GeV). ArgoNeuT is a 500 lt (175 lt fiducial) liquid Argon TPC. The TPC dimensions are approximately $0.5 \times 0.5 \times 1$ m 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 $\pm30^\circ$ to the vertical. Wire planes separation and wire-to-wire pitch are of 4 mm. Signal feed-throughs and support equipments are mounted on a flange on the top of the vessel. An external "event-flagging" 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 recording.
The experimental set-up was then moved to the MINOS Near Detector Hall about 100 m underground, just upstream MINOS-ND, to profit of it as a range stack to measure uncontained long-track muons (and pions) from muon neutrino interactions in the TPC. After remounting and LAr filling, data-taking started in May 2009 with a short technical run. From Sept.’09 up to Feb.’10 a first physics run was successfully completed, most of the time with the beam in antineutrino mode.

Main goal of the ArgoNeuT experiment is to directly measure $\nu_\mu$ 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. Considering the amount of $8 \cdot 10^{17} \text{PoT/day}$ delivered at NuMI-FNAL, the expected number of $\nu_\mu$ CC events/day has been evaluated as $N_{\text{tot}} = 117$ from the three main channels of Eq.(1) ($N_{\text{QE}} = 19$, $N_{\text{RES}} = 15$, $N_{\text{DIS}} = 83 \text{ evts/day}$). These represent the number of events per day where the interaction vertex is found inside the boundaries of the LAr-TPC active volume. According to 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 $E_\nu$ 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. During the run period $\sim 1.55 \times 10^{20} \text{PoT}$ have been delivered with about 85% live-time of the ArgoNeuT detector, i.e. $\sim 1.35 \times 10^{20} \text{PoT}$ acquired, corresponding to about 5500 $\nu$ and 3500 $\bar{\nu}$ CC events in the fiducial volume). A picture of the detector and the 2D images of a recorded neutrino event are shown in Fig.3.

Intense activity of data analysis is currently under way (reported in C. Bromberg’s talk at this Workshop). In particular, extremely detailed MonteCarlo generators are being developed for simulation and comparison with LArTPC data (FSI in MC codes represent the most difficult present challenge in MC development), as well as accurate off-line reconstruction codes for a full exploitation of the information available (3D imaging, energy/momentum reconstruction and
particle identification) from LAr-TPC data. The high identification capability of $\nu_\mu$ and $\bar{\nu}_\mu$ QE events [from the collected samples of two-tracks ($\mu, p$) and single track ($\mu$) events possibly associated to vertex activity from de-excitation mechanisms of the intranuclear cascade] may soon shed light on the FSI effects and suppress the systematic errors on the QE CC $\nu$ cross section determination on Ar target at the intermediate energies.

4. Conclusions

New generation neutrino Cross-Sections measurement is 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 US 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 LArTPC represents an ideal tool for the study of $\nu$ 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 $\nu$-beam at CERN in 1997 clearly demonstrated the capability to identify and reconstruct low multiplicity neutrino interactions.

ArgoNeuT, a 175 lt active LArTPC detector exposed to the LowEnergy NuMI beam at FNAL, has recently completed a first physics run (6 months, most in antineutrino mode, with about 10,000 events collected). Intense activity of data analysis and MC simulation is currently under way, aiming at accurate vertex reconstruction, nuclear effects and precise $\nu$-Ar cross section first determination in the intermediate energy range.

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References

[1] NuInt01 Workshop, KEK (Japan), 2001- Nucl. Phys.B - Proc.Suppl. 112, 2002.
[2] NuInt02 Workshop, UCI (US), 2002 - http://www.ps.uci.edu/~NuInt.
[3] NuInt04 Workshop, LNGS (Italy), 2004 - Nucl. Phys.B - Proc.Suppl. 139, 2005.
[4] NuInt05 Workshop, Okayama (Japan), 2005 - Nucl.Phys.B-Proc.Suppl. 159, 2006.
[5] NuInt07 Workshop, FERMILAB (US), 2007 - AIP - Conf. Proc. 978, 2007.
[6] NuInt09 Workshop, Sitges (Spain), 2009 - AIP - Conf. Proc. 1189, 2009.
[7] XX M. Born Symposium, Wroclaw (Poland), Dec. 2005 - Acta Physica Polonica B 37 n.8, 2006.
[8] MiniBooNE: http://www-boone.fnal.gov
[9] K2K - KEK: http://neutrino.kek.jp
[10] SciBooNE: http://www-scbboone.fnal.gov
[11] NOMAD Collaboration, Eur. Phys. J. C63 (2009), 355
[12] MINER$\nu$A: http://www.pas.rochester.edu/minerva
[13] ICARUS: http://icarus.lngs.infn.it
[14] ICARUS-CERN-Milano Univ. Collaboration, Phys. Rev. D74 (2006) 112001
[15] ArgoNeuT, http://t962.fnal.gov