Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Future experimental programme for neutrino cross sections

IOP Conf. Series: Journal of Physics: Conf. Series **888** (2017) 012016 doi:10.1088/1742-6596/888/1/012016

Future experimental programme for neutrino cross sections

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Abstract. The neutrino-nucleus interaction modelling is crucial for a precise measurement of neutrino oscillations. The advantages and the drawbacks of the planned strategies to measure the neutrino-nucleus cross section with different detector technologies will be discussed. The present document summarizes a talk given on these topics at Neutrino 2016 conference.

1. Introduction

The measurement of neutrino oscillations is extracted in long baseline experiments by comparing the neutrino interaction rate at near and far detectors. Such measurement is the convolution of the neutrino flux and the neutrino interaction cross section. Due to various differences between the near and far detectors (neutrino energy spectrum, neutrino flavor, acceptance and target) the flux and the cross section need to be disentangled and propagated separately from the near to the far detector. The propagation of the cross section to different neutrino energy and flavor, to different targets and phase spaces relies on neutrino interaction models which have theoretical uncertainties. The most recent T2K oscillation measurements (presented at this conference) are affected by uncertainties of 5-8%, depending on the sample (neutrino or anti-neutrino, appearance or disappearance), which are dominated by neutrino interaction systematic uncertainties. The next generation of long baseline experiments (DUNE [1], T2HK [2]) need to control the signal normalization uncertainties at the level of 1-few % in order to establish a definitive measurement of the CP violation phase in neutrino oscillations.

Many experiments will be dedicated to neutrino cross section measurements in the next decade(s) (see Tab.1). Experimentally, such measurements are complicated because the neutrino energy is not known event by event but can only be inferred from the reconstruction of all the particles in the final state of the interactions. Such reconstruction, though, suffers from limited angular acceptance, energy threshold and undetectable energy deposits (nuclear recoil, neutrons).

2. Target and acceptance

The modelling of neutrino interactions is complicated by the presence of nuclear effects in the relatively heavy nuclei used as targets in modern neutrino experiments (typically carbon, oxygen and argon). Such nuclear effects need to be measured on the different targets since they are expected to have a dependence on the size of the nucleus and the number of neutrons and

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Table 1. List of present and future experiments which will provide neutrino cross section measurements. Only the main characteristic of the technology is indicated. For instance ND280 is also composed of a scintillating target and both MINERνA and ND280 are surrounded by calorimeters.

	Magnetized TPC	Scintillator	LAr TPC	Water Cherenkov	Emulsion
Near and intermediate detectors	ND280 ND280 upgrade	INGRID WAGASCI, NOνA, DUNE(?)	DUNE(?)	TITUS NuPRISM	
Short baseline experiments			MicroBooNE SBND		
Dedicated experiments		MINERνA(-MINOS)	ArgoNeuT(-MINOS)		T60

protons. This issue may be relevant for DUNE, where the possibility of a near detector composed of multiple targets is under discussion and it is particularly important for water Cherenkov far detectors such as Super-Kamiokande and Hyper-Kamiokande which need to rely on neutrino cross section measurements on water.

Neutrino interaction measurements on water can be done interleaving the target passive water with active modules, as in the Fine Grained Scintillator (FGD) [3] or the PiZero Detector (P0D) [4] in the T2K off-axis near detector ND280 [5]. An improved design is proposed for WAGASCI [6], a detector under installation on the T2K on-axis beam and also proposed as technology for the main target of the ND280 upgrade for the T2K extended run (T2K-II) [7]. This detector is composed of a 3-dimensional grid of scintillator bars which subdivide the instrumented volume in many small boxes which can be filled with water, as shown in Fig.1. The size of each box (i.e., the number of scintillator bars for the same instrumented volume) can be tuned to reach a compromise between the tracking granularity and the fraction of water over scintillator target. The limitation of the approaches based on alternating passive water and active modules, due to overlapping of background of non-water interactions in the active modules, can be partially overcome by comparing measurements performed with the same detector filled or emptied of the water target ('water subtraction' technique) or by comparing the measurements with a similar detector where the water target has been removed or replaced by full active modules (ratio measurements). Such techniques haven been exploited in various water cross section measurements performed at ND280 [8, 9].

An alternative approach consist of making the water active by doping it with scintillator or exploiting the water Cherenkov technique, like in the large intermediate detectors ($\sim$10 kton mass, $\sim$1 km from the beam) under discussion for T2HK (TITUS [10] and NuPRISM [11]). The main limitation of such options is due to the limited reconstruction capability of water Cherenkov detectors which do not provide muon versus charged-pion discrimination, or charge discrimination and which have limited momentum resolution. On the other hand, these detectors have 4π acceptance, as do the far detectors Super-Kamiokande and Hyper-Kamiokande. Possible corrections due to different acceptance between the near and far detectors is another important source of uncertainties. In tracking detectors, such as ND280, for instance, due to the threshold of the detector for track reconstruction, most of the events have only one reconstructed track (typically the muon in Charged Current Quasi-Elastic events) and in this case it is necessary to have a measure of the time of flight (TOF) of the track in order to distinguish between a forward-going negative muons and backward-going positive muon. Such a complication effectively reduces the acceptance for backward going particles. An analogous limitation of acceptance is present in experiments like MINERνA [12] or ArgoNeuT [13] where the muon needs to be forward-going in order to reach the MINOS detector [14] for momentum measurement and charge identification. Another limitation in the acceptance, inherent to ND280, is due to the design of vertical targets (Fine Graned Detectors, FGDs) interleaved with vertical TPCs: in this configuration, the particles emitted at ~90 degrees do not cross any TPC and need to be reconstructed with a FGD only, providing very poor momentum resolution. In order to maximize the acceptance, the T2K collaboration is designing an upgrade of ND280 where the main scintillator targets are horizontal, surrounded of TPCs (as shown in Fig.2), and the detector is instrumented with TOF modules.

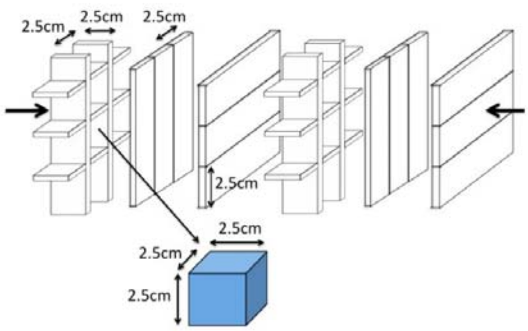

Figure 1. Schematic view of the geometrical structure of WAGASCI.

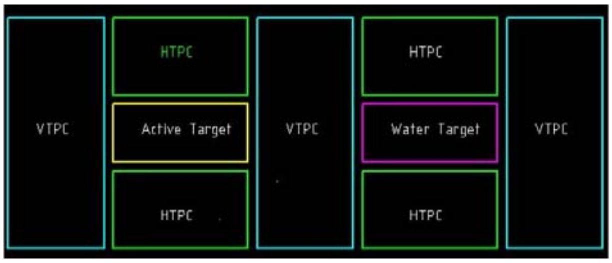

Figure 2. Schematic view of the new design under study for the ND280 upgrade. VTPC (HTPC) stands for vertical (horizontal) TPC.

It should be mentioned that even near and far detectors exploiting the same technology (as NOνA [15] or T2HK with intermediate water Cherenkov detectors) have different acceptance, e.g. on the outgoing muons, because of the different size. Moreover, even in virtually identical near and far detectors, the acceptance does not cancel out in the extrapolation because of the different momentum spectrum of final state particles, due to the different neutrino energy spectrum before and after oscillation. Finally, a precise measurement of the cross section in the largest possible phase space and for different targets is also relevant to combine the measurements from all the different experiments listed in Tab.1, as needed to reach a comprehensive understanding of neutrino interactions.

3. Proton measurements

Another promising avenue to understand and characterize the nuclear effects affecting neutrino interactions, consists in precise measurements of the outgoing protons, as done, for instance, by ArgoNeuT [16]. Similar results should be feasible, with much larger statistics, in MicroBooNE [17] and SBND [18]. Liquid Argon TPCs are indeed capable of reconstructing protons down to a momentum of ~ 200 MeV. Gas TPCs may improve further this threshold, at the expense of a smaller statistics due to the lighter target. High-Pressure TPCs promise to guarantee an optimal compromise between statistics and energy threshold. Interesting results are also expected from T60 [19], an emulsion detector placed on the T2K on-axis beam, upstream of INGRID [20]. T60 should be able to register a few thousands of neutrino interactions with very detailed tracking granularity and low threshold near the vertex, while INGRID will measure the momentum of the outgoing tracks.

Such efforts to measure the proton multiplicity and kinematics are today undermined by the very limited predictive power of the models. For instance, all the available models to describe the neutrino interactions with pairs of correlated nucleons in the nucleus (the multi-nucleon or 2p2h process) are fully inclusive on the outgoing nucleons. Even for the single nucleon interaction, the kinematics of the outgoing proton is affected by large uncertainties due to the momentum distribution of the nucleons in the nucleus before the interaction and to the re-interaction of the nucleons with the nuclear matter after the interaction. An attempt to define experimental variables which minimize the degeneracy between these different nuclear effects, allowing a clean measurement of them to improve the models, is on-going [21].

4. Calorimetric measurements and dependence on neutrino energy

Beyond the measurement of the outgoing muons and pions and of the protons above threshold, a further step consists in measuring all the energy coming out from the interaction with a calorimetric approach. Examples have been provided by MINERνA with vertex energy measurements [22, 23] and the measurement of hadronic energy [24]. This is also the main technique used in NOνA for the evaluation of the neutrino energy in the oscillation analysis (presented at this conference) and also planned for DUNE. It should be realized that the very limited predictivity of the models on the outgoing nucleons applies to this case as well. The modelling uncertainties are then tightly convoluted with calibration issues related to the energy threshold of the detector and undetectability of neutrons and nuclear recoils. This is a very complicated situation and proper caution should be applied in the interpretation of calorimetric measurements: a very good control of detector calibration and uniformity and of neutrino interaction modelling is needed since the reconstructed neutrino energy is affected by both the factors at once. A systematic bias in neutrino interaction modelling (for instance on the expected outgoing multiplicity) and a systematic under/over-estimation of the detector threshold or a mis-calibration may combine in such a way to still give a prediction of reconstructed neutrino energy which reproduces perfectly the near detector data but may give a wrong extrapolation to the far detector expectation used to extract the neutrino oscillation parameters. This is due to the fact that the mentioned factors (interaction modelling and detector calibration) have a different dependence on the total energy released in neutrino interactions and the neutrino energy spectrum at the near and far detectors are different because of the oscillations. In other terms, the neutrino modelling and the detector calibration need to be separately and precisely known, in order to be extrapolated properly as a function of energy from the near to the far detector, and the near detector measurement is, in general, not sufficient to disentangle such effects.

An alternative way to solve the problem due to the different neutrino energy spectrum between the near and the far detector has been proposed by the NuPRISM collaboration [11]. NuPRISM is a large vertical water Cherenkov detector which will span the neutrino beam at different angles, as shown in Fig.3. Different angles correspond to different neutrino energy spectra, combining the measurement from different angles is therefore possible to measure the cross section as a function of energy, or equivalently, to build a weighted combination to reproduce with NuPRISM data the same spectrum expected at the far detector after the oscillation. Such an approach would certainly minimize the uncertainty due to neutrino interactions modelling as a function of neutrino energy in the near to far detector extrapolation in T2HK. On the other hand, as previously mentioned, water Cherenkov detectors do not have the capability of a detailed reconstructions of outgoing particles, for instance neutrino and anti-neutrino interactions cannot be disentangled.

5. Electron neutrinos and anti-neutrinos

The measurement of the CP violation phase in neutrino oscillation relies on the comparison of the number of observed electron neutrinos and electron anti-neutrinos appearing at the far detector after the oscillation. Such a measurement is directly affected by the uncorrelated uncertainty between electron neutrino and electron anti-neutrinos cross sections. In the next generation of long baseline experiments (Hyper-Kamiokande, DUNE) these uncertainties need

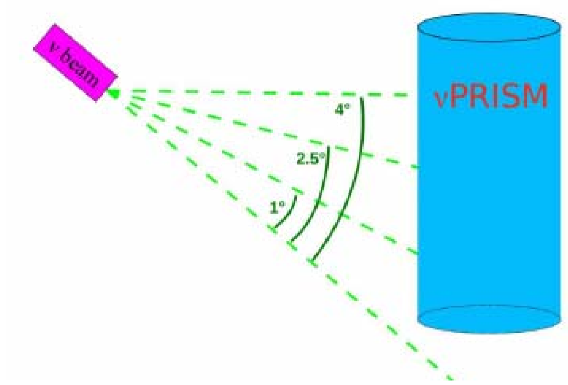

Figure 3. Schematic view of the NuPRISM concept.

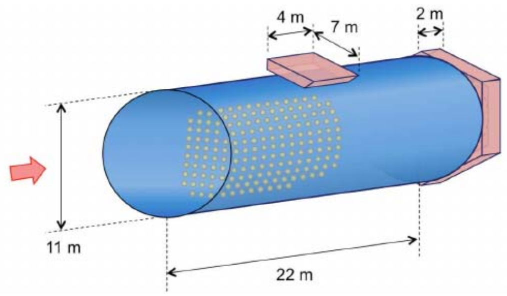

Figure 4. Schematic view of the TITUS detector. The pink boxes represent magnetized muon range detectors.

to be controlled to better than 2%: a change from 1% to 3% on such uncertainty is equivalent in terms of sensitivity to a factor two in exposure.

The main limitation in the measurement of anti-neutrino cross sections, is the presence of a large neutrino background due to the fact that anti-neutrino beams tend to have relatively large pollution of neutrinos and the anti-neutrino cross section is about three times smaller than the neutrino cross section. The rejection of neutrino backgrounds can be done effectively with magnetized detectors (as ND280 or MINOS) where the charge of the outgoing muon can be identified. For this reason, there is a proposal to instrument the T2HK large intermediate detector TITUS with magnetized Side Muon Range Detectors, as shown in Fig.4. Another option for water Cherenkov detectors, which will be tested in the next years at Super-Kamiokande, consists in doping the water with Gadolinium [25]. The Gadolinium captures the neutron produced in the anti-neutrino interaction and then emits photons with a very distinctive time delay and energy. The presence of neutrons should allow to identify anti-neutrino interactions in case of simple Charged Current Quasi-Elastic interactions:

$$\nu n \to \mu^- p \text{ versus } \bar{\nu} p \to \mu^+ n \tag{1}$$

but other interactions may cause the production of neutrons also in case of an incoming neutrino, for instance:

$$\begin{aligned} \nu n n &\to \mu^- p n \text{ (multi-nucleon interaction); and} \\ \nu n &\to \mu^- \pi^+ n, \end{aligned} \tag{2}$$

therefore such method is affected by interaction modelling uncertainties on the multiplicity of outgoing neutrons.

The measurement of electron neutrino cross section is today limited by the low available statistics since the standard beams of long baseline experiments are dominated at ~99% by muon neutrinos. To improve such measurement dedicated, new beams are needed, relying on the technology of muon storage rings (like nuSTORM [26]) which provide a similar amount of muon and electron neutrinos. Another option consists in instrumenting the line of standard neutrino beams for a precise measurement of the amount of electron neutrinos in the beam, as suggested in [27]. These options are both quite expensive.

It should be noted that there is no 'fundamental' difference in the physics of electron and muon neutrino interactions. The main difference is the larger amount of radiative corrections due to the lower electron mass with respect to the muon. No precise calculation is yet available but this should be doable with the present knowledge of QED. The other expected difference is due to known uncertainties on neutrino-nucleon interactions [28] or on nuclear effects [29] which may affect differently electron and muon neutrino interactions because of the different phase space, since electron neutrinos probe slightly different values of transferred four-momentum Q^2, for the same neutrino energy, due to the lower electron mass. It should be pointed out that, once such uncertainties properly constrained with muon neutrino interactions, the improved models may in principle be used to extrapolate to the proper phase space of electron neutrino interactions without major difficulties.

6. Conclusions

The knowledge of neutrino-nucleus interactions is crucial to guarantee the precision of the next generation of neutrino oscillation measurements but it is plagued by many uncertainties due to not well known nuclear effects. A rich programme of neutrino cross section measurements is ongoing in present experiments and planned with improved future detectors. Different technologies allow to address different aspects of the problem: dependence on the nuclear target, different phase spaces, multiplicity and kinematics of outgoing nucleons, dependence on neutrino energy. The different measurements need to be compared and, when possible, combined in order to exploit them in the most effective way to build a comprehensive understanding of neutrino interactions. In the meanwhile, a highly conservative approach should be taken in the interpretation of the near detector constraints for neutrino oscillation analyses and in the estimation of the corresponding uncertainties on neutrino oscillation measurements.

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