RECENT RESULTS ON NEUTRINO CROSS SECTIONS IN THE INTERMEDIATE ENERGY RANGE*

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Knowledge of neutrino–nucleus cross sections is very important for the neutrino oscillation measurements. The requirements for understanding neutrino interactions are becoming even greater which is due to the oscillation experiments entering the era of precision measurements. The goal of this document is to review the recent results on neutrino–nucleus cross sections. The article covers the most important experimental results from the intermediate neutrino energy regime (10s MeV–10s GeV) which were published or reported throughout the years 2013–2015.

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1. Introduction

Neutrino–nucleon cross sections are well known for the energies of the order of 10s MeV, where the inverse beta decay dominates, as well as at the energies of hundreds GeV, where the largest contribution comes from deep inelastic scattering. It appears that the knowledge of neutrino–nucleon cross sections in the intermediate energy range (10s MeV–10s GeV) is much worse. This article focuses on the experimental results concerning charged current (CC) neutrino interactions which should improve our understanding of neutrino scattering and, ultimately, our understanding of neutrino oscillations. The current, rather poor, knowledge of the CC neutrino–nucleon cross sections is illustrated in Fig. 1.

The proper modeling of neutrino interactions in the intermediate energy range is very important for the current and future long-baseline neutrino oscillation experiments. Experiments such as T2K, NOvA, DUNE are using or will use accelerator-based neutrino beams with the energies between

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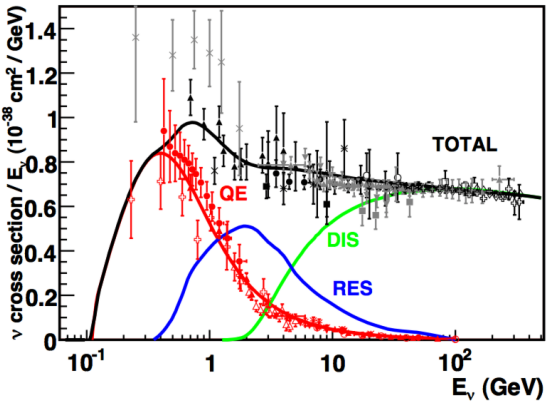


Fig. 1. Charged current neutrino–nucleon cross sections. Points represent measurements from various experiments. Monte Carlo predictions from `NUANCE` Monte Carlo generator are shown as solid lines [1].

tens MeV and tens GeV. In order to measure the CP violating phase δ_{CP} in the neutrino sector and establish the neutrino mass hierarchy, the oscillation experiments need to have their signal normalization determined with the precision better than 1%. The studies of neutrino–nucleus cross sections will help in achieving this goal.

The intermediate energy range is complicated because there are several neutrino interaction channels which contribute to the total cross section: charged current quasi-elastic scattering (CCQE), resonance single pion production (RES) and deep inelastic scattering (DIS). The results related to the first two channels (CCQE, RES) will be discussed in the following pages.

Long-baseline neutrino oscillation experiments use nuclear targets (carbon, water, iron) to increase the number of detected neutrino interactions. This fact introduces additional complications to the modeling of neutrino interactions. Nuclear effects such as: Fermi motion of the nucleons, Pauli blocking, nuclear binding energy, nucleon–nucleon correlations have to be taken into account in the calculations. The most common theoretical models which include the effects mentioned above and which are implemented in neutrino event generators are: Relativistic Fermi Gas model (RFG) [2], Local Fermi Gas (LFG) [3], Spectral Function (SF) [4], Short-Range Correlations (SRC) [5], Transverse Enhancement Model (TEM) [6], Meson Exchange Currents (MEC) [7], Random Phase Approximation (RPA) [8]. The details of these models can be found in references. Nuclear effects also affect the content and multiplicities of the particles which exit the nucleus after neutrino–nucleus interaction. Therefore, apart from a historical classification, the neutrino scattering community came up with the new way to characterize charged current neutrino interactions. Looking at the parti-

cles which are leaving the nucleus after a neutrino–nucleus interaction one can define: CC0π (or CCQE-like) — events with exactly one lepton and no charged pions leaving the nucleus, CC1π — events with exactly one lepton and exactly one charged pion, CCOther — other charged current events.

2. Overview of the neutrino scattering experiments

In this section, a short description of the experiments providing information about the neutrino scattering cross sections will be presented. More detailed description of the experiments can be found in the references. All these experiments use accelerator-based neutrino beams produced in a conventional way, where the protons from the beam hit the target and produce secondary pions which decay into neutrinos.

The first experiment is MINERvA in the United States [9]. MINERvA uses NuMI accelerator-based neutrino beam from FermiLab, which operates in two energy settings: low energy setting (LE, mean $\approx$ 3.5 GeV) and medium energy setting (ME, mean $\approx$ 6 GeV). The Detector of the MINERvA experiment is a fine-grained tracker (built of plastic scintillators) surrounded by the electromagnetic and hadronic calorimeters. MINERvA also has additional nuclear targets upstream of the main detector and uses them to measure the dependence of the cross sections on the nucleus mass number.

The second experiment is T2K in Japan [10]. T2K is primarily a neutrino oscillation experiment and uses an accelerator-made neutrino beam from J-PARC complex with the mean neutrino energy at 0.6 GeV. The experiment has two near detectors which are also used to measure neutrino cross sections: ND280 — located 2.5 degrees off the main beam axis and INGRID — the on-axis detector. ND280 consists of several sub-detectors in the 0.2 T magnetic field generated by the refurbished UA1 magnet. ND280 uses two main targets: plastic scintillator (hydrocarbon — CH) and water. INGRID is a detector with 16 modules built of plastic scintillators interleaved with iron plates. The on-axis detector is not magnetized, less precise than ND280, but has a larger mass and, apart from hydrocarbon, it also has an additional iron target.

The last two experiments described in this article are MiniBooNE [11] and ArgoNeuT [12]. MiniBooNE uses a neutrino beam from Fermilab's Booster accelerator with energies between 0.5 and 1 GeV. The detector of the MiniBooNE experiment is a Cherenkov detector filled with mineral oil (CH_2).

ArgoNeuT was a small-scale liquid argon time projection chamber (TPC) exposed to the NuMI neutrino beam with neutrino energies between 1 and 10 GeV. TPC had dimensions of $47 \times 40 \times 90$ cm^3 and 240 kilograms active mass of liquid argon.

3. CCQE-like/CC0π measurements

CCQE-like/CC0π interactions are a dominant contribution to the total cross section at the sub-GeV ($\approx$ 1 GeV) energies. These interactions also give the largest contribution to the signal sample in majority of the neutrino oscillation experiments. Moreover, quasi-elastic approximation is used in the oscillation experiments to reconstruct the incoming neutrino energy using outgoing lepton kinematics. If the modeling of CC0π interactions is wrong, then the bias is introduced into the energy calculation and, ultimately, to the oscillation parameters (oscillation formulas depend on neutrino energy).

From the experimental side, the ν_μ CCQE-like interactions can have two main signatures: 1-track, where only muon is visible in the detector and 2-track, where muon and proton are reconstructed. In 2015, the T2K Collaboration published its CCQE measurement using the on-axis detector [13]. The result of the analysis is shown in Fig. 2. T2K demonstrated that CCQE models in the `NEUT` and `GENIE` event generators are not able to describe 1-track and 2-track topologies simultaneously.

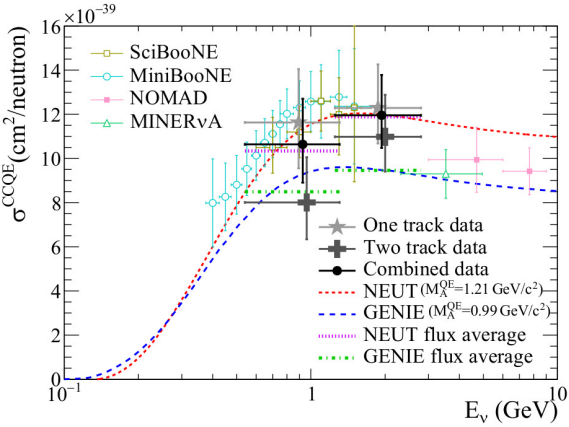


Fig. 2. Charge current quasi-elastic cross section as a function of neutrino energy. Plot shows results from T2K measurement for 1-track topology (grey star) and 2-track topology (black cross) compared to results from other experiments and Monte Carlo predictions [13].

Moreover, it appears that Monte Carlo models are not able to describe simultaneously cross sections expressed in terms of outgoing muon kinematics and in terms of outgoing proton kinematics. This fact has been demonstrated by the MINERvA Collaboration in their CCQE measurements [14]. MINERvA calculated momentum transfer Q^2 in the CCQE-like interactions with two methods: using muon kinematics only (Q^2_{QE}) and using stopping proton kinematics ($Q^2_{\mathrm{QE},p}$). The cross section calculated using muon kine-

matics $d\sigma/dQ^2_{\mathrm{QE}}$ favors RFG + TEM model in the `NuWro` event generator, suggesting the presence of the initial state nucleon–nucleon correlations (Fig. 3). The cross section calculated using proton kinematics $d\sigma/dQ^2_{\mathrm{QE},p}$ has a different preference. It favors the simple GENIE RFG model which does not contain nucleon–nucleon correlations (Fig. 4).

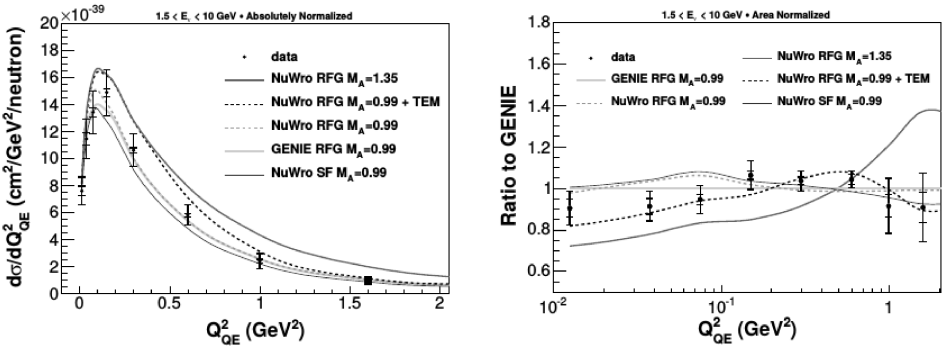


Fig. 3. CCQE cross section as a function of 4-momentum transfer Q^2_{QE} (left plot) measured by the MINERvA experiment (black points) [14]. Q^2 is calculated using outgoing muon kinematics. MINERvA result is compared with the predictions from various Monte Carlo models. Right plot shows the ratios calculated with respect to `GENIE` Monte Carlo generator.

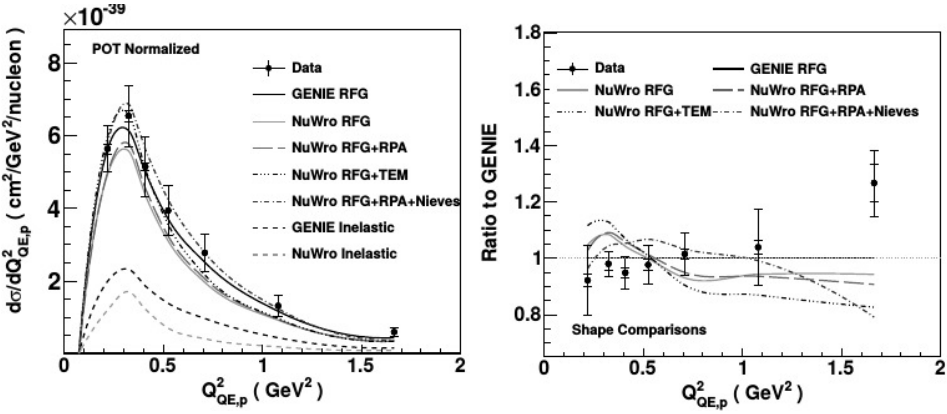


Fig. 4. CCQE cross section as a function of 4-momentum transfer $Q^2_{\mathrm{QE},p}$ (left plot) measured by the MINERvA experiment (black points) [14]. Q^2 is calculated using stopping proton muon kinematics. MINERvA result is compared with the predictions from various Monte Carlo models. Right plot shows ratios calculated with respect to the `GENIE` event generator.

In 2009, the MiniBooNE Collaboration published CCQE result [15] and reported a large discrepancy for the low neutrino energies with respect to the common Monte Carlo model which was based on RFG and included Pauli blocking. There were many attempts to explain this discrepancy, but the most convincing one is the new model, which includes the possibility of neutrino interactions with nucleon–nucleon pairs (MEC) and correlations between nucleons [16]. In 2014, the AgroNeuT experiment reported the measurement of neutrino interactions with one muon and two protons ($1\mu 2p$) in the final state of the reaction [17]. This measurement was very suggestive because such events are predicted by MEC models. Among 30 $1\mu 2p$ events recorded by ArgoNeuT there were 4 "hammer-like events" with a large angle between the directions of outgoing protons (in back-to-back configuration). The detection of these "hammer-like" events suggests that mechanisms involving short-range nucleon–nucleon correlations (SRC) are active.

The last reported CC0π measurement was performed by the T2K Collaboration [18]. T2K showed CC0π differential cross section as a function of muon kinematics and compared it to two models including MEC/$2p2h$ interactions and nucleon–nucleon correlations ([7] and [16]). The result shows that both models cannot describe the full phase space. The largest discrepancies appear in the region of the phase space where muons traverse the detector in the forward direction.

4. Single pion production results

Neutrino-induced single pion production is one of the main backgrounds to the neutrino oscillation measurements. The experimental signature of this channel is also expected to be affected by the final state interactions (FSI) of pions. Due to the presence of the nuclear target, the pions produced in the neutrino interactions can be absorbed, scattered or experience a charge exchange, which can cause transitions between observable interaction channels, such as CC1π $\rightarrow$ CC0π, and also contribute to the increase of the background in neutrino oscillation experiments. One of the goals of the neutrino scattering experiments is to measure single pion production and estimate these effects.

In 2015, the MINERvA Collaboration reported their CC1π measurement [19]. The result of the data analysis has been compared to the predictions from different neutrino event generators with FSI effects switched on and off (Fig. 5). It appears that the MINERvA result prefers theoretical models with final state interactions being active.

The T2K Collaboration presented their single pion production on water measurement at the NuFact 2015 conference. CC1π cross section as a function of outgoing pion kinematic variables has been reported. The T2K result is below predictions from the `GENIE` Monte Carlo generator, which

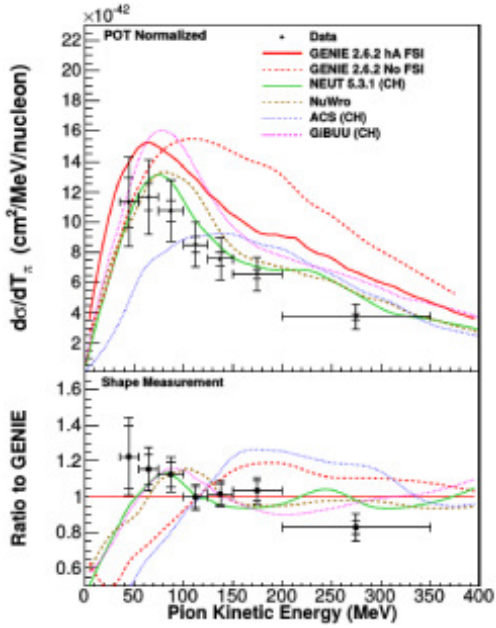


Fig. 5. Charged current single charge pion cross section as a function of pion energy (top plot) measured by the MINERvA collaboration (black dots) [19]. The result is compared to the predictions from various Monte Carlo models. Bottom plot shows ratios calculated with respect to `GENIE` event generator.

is similar to the situation observed in the MiniBooNE experiment. In the region of low angles of outgoing pion, one can observe the suppression effect which might be due to the contribution of neutrino-induced coherent pion production.

Charge current coherent pion production is another consequence of the use of nuclear targets in neutrino experiments. In this reaction, a neutrino interacts with the entire nucleus which is unfragmented and recoils as a whole with lepton and charged pion produced. The characteristic feature of this interaction is that the 4-momentum transfer to the nucleus (t) is low, *e.g.* for MINERvA it is required to be below 0.125 GeV^2.

The MINERvA Collaboration measured coherent pion production and published their result in 2014 [21]. The experiment recorded coherent pion production for both neutrinos and anti-neutrinos and reported cross section in terms of the kinematic variables of the outgoing pion. The MINERvA result shows agreement with the predictions from the `GENIE` event generator, with some discrepancies for the high pion angles.

The AgroNeuT experiment in 2014 measured for the first time charged current coherent pion cross section on argon [22]. This is an important step towards extending our knowledge on neutrino cross sections on argon, which will be widely used as a target in the future neutrino experiments, such as DUNE, MicroBooNE.

In 2015, the T2K Collaboration also reported the measurement of the charged current coherent pion cross section [20]. The experiment observed an excess of 55 ± 20 events with the significance of 2.7σ, which is the first experimental indication of coherent pion production for the neutrino energies below 1.5 GeV. T2K calculated cross section using two coherent pion production models: Rein–Seghal and Alvarez–Ruso, but the experiment has currently not enough statistical power to discriminate between them.

5. Other measurements

The last part of this document contains a description of other results such as electron–neutrino cross sections and charged current cross section ratios for various nuclei.

Electron–neutrino differential cross section for the sub-GeV neutrino energies was published for the first time in July 2014 by the T2K Collaboration [23]. The cross section has been expressed in terms of the kinematic parameters of the outgoing electron as well as the 4-momentum transfer Q^2. The T2K results agree with the predictions from the `GENIE` Monte Carlo event generator.

The MINERvA experiment reported ν_e cross section measurement at the NuFact 2015 conference [24]. The cross section represented as a function of the 4-momentum transfer agrees well with the `GENIE` prediction. MINERvA also measured the ratio of the electron–neutrino cross section to the muon–neutrino cross section as a function of Q^2. The results agree with the `GENIE` predictions within the errors.

The last measurement described in this article is related to the dependence of the neutrino–nucleus charged current cross section ratios on the size of the target nucleus. The measurement was performed by the MINERvA Collaboration [25] and the ratios to hydrocarbon (CH) were reported for three different nuclei (C, Fe, Pb) as a function of neutrino energy and reconstructed Bjorken x. The data and predictions from the simulations expressed in terms of neutrino energies agree within 1% tolerance. This fact has been also confirmed for the lower neutrino energies by the T2K experiment [26]. The problems appear when the cross section ratios are expressed in terms of the reconstructed Bjorken x variable. At low x, MINERvA observes a deficit which increases with the size of the nucleus (from C, through Fe, to Pb), while at high x, the experiment observes an excess which also

increases with the size of the nucleus. The plots also show that these results are not reproduced by the simulations. This result needs to be cross-checked by other measurements.

6. Conclusions

Neutrino cross section measurements are important to increase the precision of the measurements of neutrino oscillation parameters as well as to improve our understanding of the nature of neutrino–nucleus interactions. This article summarized the most important neutrino cross section results which were published or showed at the conferences in the 2013–2015 period.

Charge current quasi-elastic scattering is currently under change of paradigm: physicists are studying new CCQE models which include multi-nucleon processes (*e.g.* MEC/$2p2h$). Theoretical convergence is needed to predict the impact of MEC on CCQE cross section with sufficient accuracy.

Neutrino-induced pion production has proven to be an excellent probe for exploring the final state interactions of pions inside the nucleus.

Both for CCQE and CC1π — there are currently many models on the market but none of them is able to explain all available data sets. There are problems in predicting the 1-track and 2-track cross sections simultaneously as well as in explaining CCQE cross section both in terms of outgoing muon and outgoing proton kinematical variables. Data from neutrino scattering reveals many clues and certainly we need more sophisticated models and their implementations in neutrino event generators.

Interesting electron–neutrino cross section results have appeared recently. Both MINERvA and T2K report the agreement of the measured ν_e cross sections with Monte Carlo predictions.

The dependency of charge current cross section ratios on the size of the nucleus for the low Bjorken x and high Bjorken x shows discrepancies with respect to the Monte Carlo predictions. This result needs to be cross-checked by other measurements, therefore the medium energy analysis in the MINERvA experiment will be of high importance.

Finally, it is clear that apart from theoretical developments we also need more measurements with large statistics in order to discriminate between various neutrino interaction models and to reach the ultimate goal of 1% signal normalization uncertainty.

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