Neutrino scattering at low and intermediate energies – final report

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1 Introduction

The workshop "Neutrino scattering at low and intermediate energies" took place on 26-30 June 2023. The workshop was attended by 30 active participants (6 local people), out of which 33 percent were women. 40 percent were early career scientists. Almost all participants delivered a talk. 6 scientists including early career participants were assigned to lead a discussion session. We heard in total 25 talks. Each day a discussion session, led by two conveners, was very well attended. We received very positive feedback from the participants who expressed their interest in a follow-up workshop.

2 Scientific content

Our workshop was focused on neutrino-nuclei interactions at the range of tens to several hundreds of MeV. We divided topics into several sessions, as shown in Fig. 1. In this way we could smoothly transition from one theme to another and focus each of the discussion sessions differently.

We would like to emphasize that having an equal number of participants from experimental and theoretical communities allowed us to have broad discussions and various perspectives. In the following we summarize the main points raised in the talks and discussions.

2.1 CEνNS

Coherent elastic neutrino-nucleus scattering (CEνNS) was predicted theoretically decades ago but observed only very recently. The cross section for this process is relatively large and precisely calculable, making it of high interest for exotic physics searches. However, because the experimental signal for CEνNS is solely the low-energy recoil of the struck nucleus, efforts to measure this interaction channel are highly challenging.

Presently the only CEνNS experimental data are provided by the COHERENT collaboration at the Oak Ridge National Laboratory (ORNL) Spallation Neutron Source (SNS), although several other experiments are on the way. Based upon these first results, measurements on CsI and Ar, some initial limits on beyond the Standard Model (BSM) scenarios were obtained. In the future, the uncertainty on the measured cross sections will be much reduced, most importantly by constraining the flux, as well as by improving the statistics. The planned Second Target Station at the SNS will allow for significant expansion of the ORNL experimental program with low-energy neutrinos.

To further improve the usefulness of CEνNS as a probe of BSM physics, it is important to better understand the theoretical uncertainty, particularly the nuclear form factors. Under scenarios involving non-standard neutrino interactions, these would contain an additional contribution which must be distinguished from the Standard Model expectation.

Currently, the theoretical CEνNS calculations for relevant heavy nuclei, together with the estimation of non-standard form-factors, were performed within the shell-model framework. A calculation of ^{40}Ar weak form factors from first-principles is also available.

The uncertainty of the theoretical calculations could be still improved by ab-initio approaches in which various sources of theoretical errors can be analysed. In particular, the uncertainties coming from the nuclear Hamiltonian can be propagated to the final results using Bayesian analysis.

Monday	Tuesday	Wednesday	Thursday	Friday
Elastic + inelastic 10s MeV	Elastic + inelastic 10s MeV	Electrons for neutrinos	MC generators	Intermediate energies (theory)
Elastic + inelastic 10s MeV	Intermediate energies (nu experiments)	Intermediate energies (nu experiments)	Intermediate energies (theory)	

Figure 1: Distribution of scientific themes during the week.

2.2 Inelastic scattering of tens-of-MeV neutrinos

Inelastic neutrino-nucleus scattering at tens-of-MeV energies is sensitive to nuclear structure details like the low-energy excitation spectrum and giant resonances, making theoretical predictions particularly difficult. Total cross section predictions can differ by a factor of 2 or more. Theoretical uncertainties related to other relevant observables are also large but difficult to quantify at present.

A major application for better understanding these reaction processes is the interpretation of a future observation of supernova neutrinos with large detectors like DUNE and Hyper-Kamiokande. Sensitivity to the supernova ν_e flux in particular is enabled only by inelastic charged-current scattering on complex nuclei (Ar for DUNE, O for Hyper-K). Enabling reliable reconstruction of the ν_e energy spectrum requires modeling not only the inclusive cross section but also various details of the final state such as neutron emission.

The main software tool currently used to simulate tens-of-MeV neutrino scattering on complex nuclei is a Monte Carlo event generator called MARLEY. All DUNE supernova sensitivity studies are based on MARLEY simulations, and the code has been used by other experiments as well. We discussed the physics implementation of MARLEY and explored ways that some of its presently rough approximations may be overcome in future development.

We also discussed recent results from the COHERENT collaboration, which performed measurements of the inclusive charged-current ν_e cross section on ^{127}I as well as neutrino-induced neutron production on a Pb target. Tensions with existing theoretical predictions, including but not limited to MARLEY simulations, illustrate the need for increased attention from the theory community.

Ideally, the new model calculations should be extensively benchmarked. There are, however, very scarce data available. A possibility of using muon capture data as an indirect probe of the relevant matrix elements was raised several times during the workshop. It would be also valuable to have electron scattering data at lower energies to constrain the contribution from the vector part of the electroweak current. This could be provided in the future MESA facility, which will operate at energies up to 150 MeV. ^{16}O and ^{40}Ar targets are of particular importance for the future Hyper-K and DUNE physics programs. Both inclusive and exclusive measurements would be valuable to pursue.

To have maximal impact, the theoretical models need to be interfaced with the Monte Carlo event generators used by experimental collaborations. We explored some next steps to enable more advanced theoretical models to be incorporated into MARLEY.

2.3 Electrons for neutrinos programs

The idea of using electron scattering experiments to infer information for neutrino-nuclei interactions is very well established. During this workshop we heard a review of the world-leading efforts of electron scattering facilities around the world to produce new measurements which are of most relevance in targets and energies to the next generation of neutrino oscillation experiments. Out of the three operating electron beam experiments

(Hall-A spectrometers, Hall-B CLAS detector at Jefferson Lab, and MAMI at JGU, Mainz), MAMI operates at lower energies and can provide invaluable data for the lowest-energy kinematic region. These data will be complementary to those obtained from other sources and a valuable asset to the worldwide neutrino program.

The capabilities of MAMI and the future MESA facility were presented, and a lively discussion followed about possible new collaborations.

2.4 Intermediate energy transfers

In the energy range of long-baseline neutrino oscillation experiments below the Delta resonance peak, there is still much room for improvement of our understanding of neutrino-nucleus interactions.

2.4.1 Neutrino experiments

We heard about the latest results from several current neutrino experiments, from T2K in Japan to MicroBooNE in the US. Each paves the way to a next-generation neutrino experiment (Hyper-K and DUNE respectively). Special attention was given to single-proton knockout cross sections from MicroBooNE, a channel in which the energy reconstruction of the incoming neutrino is relatively easy.

During this session we also heard several talks about future programs. The SBND (Short Baseline Near Detector) experiment at Fermilab will soon provide much more detailed cross-section data in the neutrino energy region of 1 GeV, which will allow a better understanding of the nuclear cross sections. The ANNIE (Accelerator Neutrino Neutron Interaction Experiment) experiment will focus on the detection of neutrons. These are notoriously difficult to measure in most other detectors and are a main driver of cross-section-related uncertainties for neutrino oscillation measurements. Lastly, we heard about some prospects for the future ESSνSB experiment in Sweden, which similarly to DUNE and Hyper-K would aim at measuring CP violation in neutrino oscillations.

2.4.2 Monte Carlo generators

In addition to the talk in the low-energy session about MARLEY, we also had presentations and discussion about neutrino interaction simulations at the higher energies relevant for accelerator neutrinos. A large emphasis was given to two topics.

The first is the modeling of the intranuclear cascade in the Monte Carlo event generators. We discussed various approaches employed by MC generators, some possibilities of improving the modelling, and new data (exclusive measurements) which could serve to further constrain and benchmark the cascade models.

The second topic was parameter tuning in MC generators. Various strategies used by the T2K and $e4\nu$ collaborations were explored. There was also discussion of the observables that can best constrain different aspects of the simulation model and what further input from theorists would be most useful.

2.4.3 Theoretical models

We heard about theoretical efforts from various groups. This included the more phenomenological approach of the Valencia group, as well as some new results obtained using the relativstic mean-field model for both 1- and 2-body currents. Ideas were shared on how to employ some ab-initio methods to address exclusive processes, including strategies based upon the short time approximation and the spectral function approach. Finally, we heard about recent results and progress made from the ab-initio approaches based upon quantum Monte Carlo and coupled-cluster methods.

Epilogue

The organisers would like to thank the MITP for the hospitality and for fostering knowledge sharing between various communities. Your help and support enabled a successful collaboration to improve our understanding of neutrino scattering at low and intermediate energies. The topics discussed at this workshop will help guide us in our efforts to maximize the physics sensitivity of the next generation of accelerator-based neutrino oscillation experiments.