Snowmass2021 - Letter of Interest

Electron scattering and neutrino programs

NF Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
□ (NF4) Neutrinos from natural sources
□ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
□ (NF7) Applications
■ (NF8/TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
□ (Other) *[Please specify frontier/topical group(s)]*

Contact Information for corresponding author:
Kendall Mahn (Michigan State University) [mahn@msu.edu]:

Authors: A. Ankowski, O. Benhar, A. Friedland, A. Furmanski, L. Kaufman, W. Ketchum, S. Li, T. Lux, K. Mahn, S. Manly, C. Mariani, K. S. McFarland, O. Moreno, T. K. Nelson, V. Pandey, E. Radicioni, F. Sanchez Nieto , P. Schuster, H. A. Tanaka, N. Toro, N. Tran, Y.-T. Tsai

Abstract: In this Letter-of-Interest, we describe the important role of electron-nucleus ($e-A$) scattering experiments in an era when current (NOvA, T2K) and future (Hyper-Kamiokande, DUNE) accelerator-based neutrino oscillation experiments will depend on precision modelling of the corresponding neutrino-nucleus $\nu - A$ process to achieve their goals. The benefits also apply to other measurements which use neutrinos as signal or background in a similar energy regime, including exotic and beyond-the-Standard-Model physics searches. We briefly describe the necessity of these measurements, ongoing efforts, and potential future measurement programs at various facilities around the world.

1 Motivation

As accelerator-based neutrino experiments probe neutrino oscillation parameters with increasing precision and seek the first glimpse of qualitatively new phenomena (*e.g.*matter effects and CP violation), the demands on accurate modeling of neutrino-nucleus ($\nu - A$) interactions have steadily increased[1]. Systematic uncertainties associated with the assumed $\nu - A$ model used in these experiments are among the most pernicious challenges for the current generation of experiments (NOvA and T2K), and the needs will be even more acute for next generation experiments (Hyper-Kamiokande and DUNE). In the meanwhile, $\nu - A$ experiments such as MINERvA and near detectors for long-baseline experiments (*e.g.* ND280 at T2K) have produced a new generation of measurements which have allowed detailed comparison to model predictions. However, it is clear that much work remains in light of the ever increasing demands from neutrino oscillation experiments and the current unsatisfactory state where no $\nu - A$ model can successfully accommodate the available measurements. Furthermore, $\nu - A$ models are also essential to a wide variety of physics searches which use neutrinos as signal (e.g. sterle neutrinos) or background processes (e.g. searches for light dark matter).

The critical role of $e - A$ scattering in this process can be viewed in two ways:

- $e - A$ scattering provides fundamental input into the modelling of $\nu - A$ interactions. In particular, the vector response in $\nu - A$ interactions is related to $e - A$ scattering via the conserved vector current, and hence the relevant form factors in any $\nu - A$ model are derived from $e - A$ data.
- $e - A$ scattering provides a fully analogous process to $\nu - A$ scattering and probes many of the same issues in nuclear modelling (initial state dynamics, multi-nucleon effects, final state interactions, etc.) and thus provides a testing ground for any model of $\nu - A$ interactions.

Taken together, the ability of $\nu - A$ models to reproduce $e - A$ scattering measurements can be considered a requirement. Further more, in contrast to the virtually uncontrolled initial state of a $\nu - A$ interaction, $e - A$ scattering offers the opportunity to probe many of the same nuclear effects with a firm handle on the initial electron energy and the energy/momentum transfer in the interaction. In contrast, given the unknown incoming energy of an (accelerator-produced) $\nu - A$ interaction, such control over the event kinematics can only be obtained as an average over the incident neutrino spectrum, with any attempt to isolate the kinematics requiring the use of model-dependent observables.

2 Measurements

$e - A$ scattering is a major field in its own right, with a number of facilities and experiments enabling a wide range of measurement techniques. Measurements can be roughly categorized as

- inclusive ($e + A \rightarrow e + X$):only the outgoing electron kinematics measured, effectively summing over all hadronic final states X.
- semi-inclusive ($e + A \rightarrow e + x + X$): where in addition to the electron, some subset x of the final state particles are targeted for reconstruction.
- exclusive: where in addition to the electron, a particular final state is targeted for full reconstruction.

Each method is of value for neutrino physics, but the perspective and needs from $\nu - A$ may be different given the goal of producing a model that is fully inclusive in the lepton kinematics and also the possible exclusive hadronic states.

3 Needed capabilities

Since we cannot control the final state in a neutrino interaction, the relevant $e - A$ scattering measurements for $\nu - A$ span a wide range of phase space. Conversely, since we can control the kinematics in $e - A$, a measurement program that provides full information on the cross section and hadronic states at each relevant point in phase space is desired. While existing $e-A$ experiments provide important information, dedicated measurements to support $\nu-A$ modelling are needed, particularly with regard to experiments that can reconstruct the wide variety of hadronic final states that result from $e/\nu-A$ scattering in this energy region. Likewise, $e-A$ experiments study a wide range of target nuclei; these are typically useful for $\nu-A$ modelling, but for neutrino oscillation experiments some target nuclei (C, O, Ar) are more equal than others. In the US, the divide between the nuclear and high-energy physics communities and funding has been a formidable barrier towards mobilizing a program of $e-A$ measurements directed towards the needs of $\nu-A$ modelling, with a few notable successes in accessing the necessary run time and data[3;4].

With regard to the two major future long baseline neutrino oscillation experiments, some basic needs include:

- Hyper-Kamiokande: Measurements on $(H_2)O$, with electron energies in the ~ 1 GeV range, probing final states through the single pion production region.
- DUNE: Measurements on Ar, with electron energies in the several GeV range, extending into the transition and deep-inelastic scattering region.

Both will also observe atmospheric neutrinos from the quasi-elastic regime up to deep-inelastic scattering.

3.1 Accelerator and Experimental Facilities

A number of facilities exist that provide electron beams and experimental halls useful to advance the modelling of $\nu-A$ scattering:

- JLAB: Large data set on ^{3}He, ^{4}He, C and Fe taken with 1, 2, and 4 GeV beams using the CLAS spectrometer, including inclusive, semi-exclusive and exclusive channels. New experiment approved using upgraded CLAS12 spectrometer, with enhanced neutron detection capabilities and lower scattering angle (i.e. lower momentum transfer) coverage; it will use relevant targets to neutrino experiments (C, O, and Ar), at a range of beam energies (1, 2, 4, and 6 GeV). First data taking expected summer 2021.
- MAMI: Up to 1.6 GeV electron beam at the University of Mainz (Germany).
- S30XL: 4 GeV electron beam at SLAC running fully parasitically with LCLS2, with a planned upgrade to 8 GeV that has recently been approved. Experiments include LDMX[5], a beam-based dark matter search using missing momentum techniques. It will have precise kinematic measurements of the electron over a range of angles and will also have the capability to reconstruct a variety of hadronic final states[2] there is also opportunity for additional detectors and experiments in the hall.

The beams at the various facilities also offer complementarity in their currents and time structures.

4 Conclusions

A continuing program of electron scattering measurements, some dedicated to the needs of $\nu-A$ modelling, will be important to support the needs of the neutrino community by providing essential foundations for $\nu-A$ modelling and validating any modelling framework/generator. It will offer a rich and exciting program of measurements that will complement the ongoing global $\nu-A$ experimental program and offer a deeper and more unified view into nuclear dynamics relevant for the neutrino oscillation program. Resulting $\nu-A$ modelling improvements will also provide important benefits to exotic and beyond-the-Standard-Model physics searches that either use neutrino interactions (*e.g.* sterile neutrinos and non-standard interactions) or have neutrino interactions as background (nucleon decay, dark matter searches) and may prove critical for a definitive discovery. Facilities such as JLAB offer existing experimental setups where measurements can be made, while others like MAMI allow a dedicated experiment to serve the needs of $\nu-A$ modelling to be designed and built from scratch. Upcoming facilities like S30XL at SLAC offer both an experiment (LDMX) where relevant measurements can be made while also providing the opportunity for new experiments. It is important for the community to carefully plan a program of measurements as we look to ever more ambitious neutrino experiments that rely on accurate $\nu-A$ interaction modelling.

References

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