Nuclear Theory and the U.S. Experimental Neutrino Physics Program

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I. EXECUTIVE SUMMARY

The neutrino has shown itself to be a much more complicated particle than expected; it has flavor states composed of an oscillating mixture of mass eigenstates. In the United States, significant investment is being made to further investigate this profound behavior of the neutrino. In particular, our sights are set on precisely testing the current 3-neutrino mixing picture and determining whether or not neutrinos violate CP, the latter of which can only be tested with accelerator-based sources of neutrinos. In accelerator-based neutrino oscillation experiments, the goal is to measure the appearance and/or disappearance of a given neutrino flavor as a function of the incident neutrino energy. The signal for appearance or disappearence can be the observation of an exclusive process or inclusive production of a particular neutrino flavor in the detector. In both cases, the neutrino is interacting with a complex nucleus.

Neutrino oscillation experiments are currently evolving from the discovery to the precision stage and therefore understanding the challenging role of the nucleus in neutrino interactions has become essential. The presence of neutrinos, being chargeless particles, can only be inferred by detecting the secondary particles created when the neutrinos interact with the nuclear targets used as detectors. A better understanding of neutrino interactions with nuclei is then crucial to classify signal from background and minimize systematic uncertainties in our neutrino oscillation investigations.

Understanding the subtleties of the nuclear environment and its effects on what neutrino experimentalists measure in their detectors can only be accurately performed with the input of nuclear physics theorists specializing in this topic. NuSTEC (Neutrino Scattering Theorist Experimentalist collaboration) is a currently forming collaboration that seeks nuclear theorists to join neutrino experimentalists in working toward this goal. NuSTEC has already enlisted nuclear theorist expertise in the recent successful NuSTEC Training in Neutrino Nucleus Scattering Physics (http://nustec2014.phys.vt.edu). The next step is encouraging the participation of individual nuclear theorists and neutrino experimentalists in together exploring neutrino-nucleus scattering with the goal of producing a complete calculation that can be employed in neutrino-nucleus scattering event generators such as GENIE. This has been done very successfully in the recent past by an international collaboration of 31 experimentalists and theorists [1] that has successfully proposed a new electron scattering experiment on argon at Jefferson Lab to further develop the spectral function nuclear model for argon. A second collaboration is concentrating on the Valencia model including random phase approximation (RPA) and meson exchange current (MEC) effects in the kinematic regime applicable to the T2K and MINERvA experiments [2–4]. A third example is the basis for a whitepaper on Green's Function Monte Carlo techniques by a collaboration of ANL, Jefferson Lab, and Los Alamos theorists with Fermilab experimentalists. **We request support of such collaborative NP-HEP efforts by the nuclear physics community in the NSAC long-range program.**

II. NEUTRINO-NUCLEUS STUDIES AND OSCILLATION PHYSICS

Neutrino oscillations depend on the distance the neutrino has travelled and the energy of the neutrino, E_ν. A majority of experiments determine oscillation parameters from the neutrino energy spectrum after oscillations have occurred. As one example, in the case of ν_μ disappearance, the mixing angle θ_{23} is inferred from the "dip region" in the neutrino energy spectrum where the survival probability of $\nu_\mu \to \nu_\mu$ is close to zero. What experiments measure however, is never the true neutrino energy (E_ν), but instead the neutrino energy ($E_\nu^{\rm rec}$) reconstructed from the final state particles in charged current (CC) neutrino interactions, either from calorimetric estimations of the hadronic system and/or lepton kinematics.

Current generation neutrino oscillation experiments have a growing need for improved neutrino-nucleus model development and uncertainty estimation. The neutrino-nuclear interaction (cross section) model is critical in oscillation measurements as it determines the relationship between E_ν and $E_\nu^{\rm rec}$. We are choosing the Tokai-to-Kamioka (T2K) experiment as an example to illustrate this point because it is the experiment that is providing what is currently the most precise ν_e appearance measurements and hence is a good test case. Table I [5]

Source of uncertainty (number of parameters)	δn^{exp} / n^{exp}
ND280-independent ν cross section (11)	4.9%
Flux and ND280-common ν cross section (23)	2.7%
SK detector and FSI+SI systematics (7)	5.6%
$\sin^2(\theta_{13})$, $\sin^2(\theta_{12})$, Δm^2_{21}, δ_{CP} (4)	0.2%
Total (45)	8.1%

TABLE I. Effect of 1σ systematic parameter variations on the expected number of events at the far detector in the T2K disappearance analysis, assuming oscillations corresponding to $\sin^2(\theta_{23}) = 0.500$ and $|\Delta m^2_{32}| = 2.40 \times 10^{-3}$ eV$^2/c^4$. FSI = Final State Interactions and SI = Secondary Interactions, which are reinteractions of the pion in detector medium outside the nucleus. Reproduced from [5].

summarizes the uncertainties in the world's best measurement of θ_{23} by the Tokai-to-Kamioka (T2K) experiment [5]. A significant portion of the total uncertainty (8.1%) is due to cross section systematic uncertainties which did not cancel in the near/far extrapolation (4.9%). While T2K's analyses are still statistics limited, from a recent paper on T2K's sensitivity assuming design (7.8×10^{21}) POT is achieved, for a "measurement of θ_{23} and $|\Delta m^2_{32}|$, the systematic error sizes are significant compared to the statistical error" [6]. Currently, the least well-known mixing angle (apart from δ_{CP}) is θ_{23}, so improvements to the systematic uncertainty for T2K will improve measurements of θ_{23} and $|\Delta m^2_{32}|$ and affect how we interpret ν_e and $\overline{\nu}_e$ appearance measurements to determine neutrino CP violation and the ordering of the neutrino mass eigenstates (mass hierarchy). Future programs, such as the Experiment at the Long-Baseline Neutrino Facility (ELBNF), formerly the Long-Baseline Neutrino Experiment [7], rely on uncertainties of 1% (5%) on signal (background) to achieve their stated physics goals. Note that future experiments are proposed on nuclear targets (water, argon) and will require an understanding of neutrino and antineutrino interactions on nuclei for all flavors.

The uncertainties in the T2K ν_μ disappearance and ν_e appearance analyses are driven by disagreements between external neutrino scattering data and outdated models used in neutrino event generators. For T2K's flux ($E_\nu \sim 0.6$ GeV), the most significant processes are charged current quasi-elastic (CCQE, naively, $\nu_l\, n \rightarrow l^-\, p$, $\bar{\nu}_l\, p \rightarrow l^+\, n$) interactions and resonant single pion production (CCπ) dominated by Δ production. T2K's analysis relies on a parameterized cross section model, determined from fits to external neutrino scattering and pion scattering data [8] and comparisons to alternate models. External data is not well represented by the nuclear model in NEUT, the neutrino event generator used by T2K, resulting in puzzles [9] which need resolution. **Nuclear theory insight can be used to guide which models best represent external data, aid in generator implementation, and provide suitable parametrizations that encompass realistic theoretical uncertainties on the model.**

III. IMPACT OF HADRONIC AND NUCLEAR PHYSICS IN NEUTRINO EXPERIMENTS

The experience gathered during decades of hadronic and nuclear physics research has allowed the development of more precise and complete neutrino interaction models, identified new relevant reaction channels, and provided a more realistic description of the nuclear ground state and final state interactions. In collaborations between neutrino experimentalists and nuclear theorists, these more advanced models need to be implemented consistently in the simulations employed in the analysis of experimental results. This wealth of pion, photon and, particularly, electron scattering data such as nucleon and nucleon-to-resonance transition electromagnetic form factors, pion-nucleon scattering amplitudes, nuclear parton distribution functions, in-medium modification of hadronic states, and multi-nucleon reaction mechanisms provide valuable input as well as validation for neutrino cross section models.

A clear example of this synergy has emerged in connection with recent CCQE measurements on nuclear targets performed by the MiniBooNE experiment [10]. Only after taking into account two-nucleon mechanisms (two-particle-two-hole excitations) has it been possible to reconcile these experimental results with the, admittedly limited, information on the nucleon axial form-factor available from neutrino scattering on deuterium and pion electroproduction [11–13]. These two-particle-two-hole excitations mechanisms also help describe the dip region between the quasi-elastic and $\Delta(1232)$ peaks observed in electron scattering [14]. These findings have important implications for neutrino-oscillation experiments as a source of systematic error in the determination of the neutrino energy, which is not known for the non-monochromatic neutrino beams. In the recent T2K collaboration study of the effect of multinucleon processes in the analysis, a bias of 0.2-2.9 % in the value of θ_{23} was reported. Other analyses report a larger bias in the inferred oscillation parameters [15–17]. This scenario calls for a more direct experimental signature of multi-nucleon processes. However, the primary distributions will be heavily distorted by final state interactions and, therefore, model discrimination would require a high precision and considerable improvements in the Monte Carlo simulations.

By combining the principles of low energy effective field theories of strong interactions and phenomenology, important progress has also been made in the theoretical description of relevant inelastic reaction channels such as pion [18, 19] and single-photon emission [20–22]. Strangeness and η meson production have also been investigated [23–25]. The partial conservation of the axial current has been exploited to obtain the forward neutrino cross sections using a dynamical coupled channel model that successfully fits a large set of pion-nucleon and photon-nucleon data [26]. A challenge for the new generation of neutrino experiments is to achieve a realistic description of the poorly known resonance region and establishing a better connection with the deep inelastic regime.

The precision required to achieve our future goals in neutrino physics demands a more rigorous description of the nuclear ground state beyond the relativistic global Fermi gas model in wide-spread use in present neutrino event generators. More advanced descriptions of neutrino interactions based on the local Fermi gas [27], shell model, relativistic mean field [28, 29] and spectral functions [17, 30, 31] have been developed. The spectral function approach is now being developed also for the two-particle-two-hole excitations. This new development, if successful, would represent an important step toward the development of a consistent treatment of nuclear effects in neutrino interactions simulation. Another important benchmark is provided by the ab-initio Green's Function Monte Carlo framework (GFMC), within which the sum rules of the weak neutral current response functions on nuclei up to ^{12}C have been recently obtained [32, 33]. It has also been shown that the scaling properties exhibited by inclusive electron-nucleus scattering data can be used to predict neutrino-nucleus cross sections [34]. Transport theory has been applied to describe a large variety of semi-inclusive and exclusive reaction channels such as nucleon knockout, pion and strangeness production from nuclear targets [35]. It is important to realize that a relevant fraction of the final-state particles are produced in secondary collisions in the nuclear medium. **A demanding task standing ahead is to provide resources to complete the new developments and to integrate them in a consistent framework that is flexible and fast enough to meet the needs of experimental analyses.**

IV. IMPACT OF NEUTRINO CROSS SECTION MEASUREMENTS IN HADRONIC AND NUCLEAR PHYSICS

Recent years have witnessed an intense experimental and theoretical activity aimed at a better understanding of neutrino interactions with nucleons and nuclei. A wealth of data exists through measurements of CC and NC processes made by ArgoNeuT [36], MINERvA [37], MiniBooNE [38], MINOS near detector [39], NOMAD, SciBooNE [40], and T2K near detectors [41]. In addition, the MicroBooNE experiment and NOvA near detector are beginning operation, and new experiments have been proposed (CAPTAIN-MINERvA, LAr1-ND [42], nuPRISM [43]). These experiments span a range of neutrino and antineutrino beam energies and target materials. Although this activity has been stimulated mostly by the needs of neutrino oscillation experiments in their quest for a precise determination of neutrino properties, the relevance of neutrino interactions with matter extends over a large variety of topics, including hadronic and nuclear physics.

Neutrino cross section measurements permit the investigation of the axial structure of the nucleon and baryon resonances, enlarging our views of hadron structure beyond what is presently known from experiments with hadronic and electromagnetic probes and lattice QCD. In the recent past, the electromagnetic form factors of the nucleon have been extensively studied at JLab with unexpected results such as the differing dependence of the electric and magnetic proton form factors over the Q^2 range from 1 to 8.5 GeV^2 and their deviation from the approximate dipole behavior at $Q^2 > 1$ GeV^2 [44]. In contrast, the experimental information about the axial nucleon form factors is scarce. The existing data from neutrino quasi-elastic scattering on deuterium and pion electroproduction are compatible with a dipole behavior which is not well justified from a theoretical point of view [45]. In the case of the electromagnetic form factor, the dipole behavior arises from cancellations between monopole terms that appear naturally in the vector meson dominance picture. In the axial sector, a similar scenario might be in place from the interplay of two or more axial mesons [46]. It should be stressed that the contribution of the term proportional to the axial form factor to the parity-violating asymmetry in electron-proton elastic scattering with polarized beams is typically orders of magnitude smaller than the dominant (magnetic) one. The most direct way to measure the axial form factors is with neutrino scattering.

Another fundamental and open question is the strangeness content of the nucleon axial form factor. Indeed, if the s and $\bar{s}$ distributions in the nucleon are similar, such a form factor can arise. If non-zero, the strangeness content of the nucleon spin, $\Delta s = G_A^s(0)$, can change the neutral current elastic cross section on protons and neutrons appreciably. The MiniBooNE experiment performed a detailed study of neutral current nucleon knock-out on mineral oil (CH_2) but their measurement turned out to be rather insensitive to Δs because of large uncertainties in the response to scintillation light in the detector and difficulties in distinguishing between protons arising from the interaction of neutrinos and neutrons [47]. The situation is different for the forthcoming MicroBooNE experiment, where a reliable identification of low energy protons knocked out of argon will be possible, as reported by the ArgoNeuT experiment [36]. As a result, the error in the determination of Δs would be drastically reduced [48]. Nevertheless, it should be recalled that the presence of multi-nucleon contributions, together with final state interactions [49, 50] will certainly affect the extraction of Δs and should be carefully studied.

The interest in quasi-elastic axial form factors also encompasses the nucleon-hyperon transitions accessible with antineutrinos via Cabibbo-suppressed transitions $\bar{\nu}_l\, N \rightarrow l^+\, Y$, $Y = \Lambda\,,\, \Sigma^{-,0}$. Hyperon semi-leptonic decays allow the extraction of the CKM matrix elements and might reveal interesting physics beyond the Standard Model [51]. Complementary information about the axial current from neutrino reactions can help to reduce the systematic uncertainties in these studies.

Understanding the excitation spectrum of the nucleon, and the properties of baryon resonances in general, is a central question in strong interaction physics. Our knowledge about this spectrum was originally provided by elastic pion-nucleon scattering however recent experiments at MAMI, ELSA and JLab with photons and electrons have also unraveled the electromagnetic properties of baryon resonances. To make this possible, detailed measurements of pion photo- and electro-production, as well as other inelastic channels ($\pi\pi N$, ηN, associated strangeness production) have been analyzed with state-of-the art coupled channel interaction models [52–55]. In contrast, the axial sector is practically unknown. Progress in this direction requires new and more precise measurements of neutrino inelastic scattering on hydrogen and deuterium targets. **The information available from modern experiments on nuclear targets is valuable but the uncertainties introduced by nuclear effects, final state interactions, and the fact that the neutrino energy is not known on an event-by-event basis make the interpretation of such data very challenging. NuSTEC provides a mechanism to coordinate the work of nuclear theorists with experimentalists on the relevant collaborations to clarify disagreements between datasets and model predictions.**

For nuclear physics, the fact that neutrino experiments are performed with nuclear targets represents a challenge but also an opportunity as neutrino-nucleus interactions incorporate new and important information due to the presence of both axial and vector currents. They provide an excellent testing ground for models of the axial response. It is interesting to elucidate the role of multi-nucleon mechanisms, in particular meson exchange currents which are different than in the case of electromagnetic probes; the same is true for long-range correlations because the axial current gets renormalized in the nuclear medium in a different way than the vector current. Modern experiments, most notably MINERvA [56], will measure different nuclear targets with the same (anti)neutrino flux, and the suite of current and proposed experiments include light (CH,H_2O) and heavy nuclei (Ar, Fe and Pb), which will provide important clues about the mass dependence of different observables. Novel approaches are also being investigated experimentally, such as the generation of pseudo-monochromatic beams on a single target material akin to electron-scattering (nuPRISM detector [43]).

V. CONCLUSIONS

The precision era of neutrino oscillation physics and the use of nuclear targets has solidly forced us into a regime where nuclear effects are important and must be better understood to extract necessary information from our neutrino data samples. The strong-interaction physics in play alters final state particle compositions and kinematics, determination of the incident neutrino energy, and neutrino versus antineutrino scattering. For example, if neutrinos and antineutrinos experience different nuclear effects, this will directly impact ones ability to definitively test for the presence of CP-violating effects in the data. Improved theoretical calculations and better experimental data on neutrino-nucleus interactions are emerging, but at present, they tend to raise more questions than they answer. **Moving forward, increased collaboration between theorists and experimentalists and HEP and NP is essential to ensure that we match the ambitions of the neutrino oscillation program. The time is now to forge these crucial collaborations and meet this need.**

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