Snowmass2021 - Letter of Interest

Theoretical predictions of Neutrino-nucleus Interactions

NF Topical Groups:

■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
■ (TF05) Lattice gauge theory
■ (TF11) Theory of Neutrino Physics
■ (CompF2) Theoretical Calculations and Simulation

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Abstract: A central goal of neutrino oscillation experiments, such as DUNE and HyperK, is to discover CP violation in neutrino mixing. If observed, it could, through leptogenesis, provide a mechanism to explain the observed matter-antimatter asymmetry in the universe. For the DUNE experiment to reach its design precision, it needs $< 2\%$ accuracy in the neutrino-nucleus cross-section over the range $\approx$ 300 MeV to $\approx$ 5 GeV in momentum transfer[5]. Since the final state of the struck nucleus (a complex ^{40}Ar nucleus) is not fully resolved experimentally, but reconstructed using event generators relying on nuclear models, the uncertainties can be large and uncontrolled. Our goal is to improve and constrain these nuclear models with input from lattice QCD and with state-of-art calculations of nuclei. Nuclear models use input starting with the four form factors that describe neutrino-nucleon interaction (single nucleon matrix element), matrix elements of the weak current between 2 nucleons, nucleon-pion, and higher states. This LOI provides the motivation for the calculations; a brief summary of the status of nuclear models, lattice QCD calculations, and PDFs; and an outlook on work to be done for improvements and progress.

Motivation: The lack of antimatter in the observed universe is one of the most profound mysteries of nature. The combination of the standard models of particle physics and the standard cosmological model cannot account for the observed baryon asymmetry of the universe. New and much larger sources of $\not{C}\not{P}$ are needed to explain the dynamical generation of this asymmetry. Two promising mechanisms are a maximal CP violating phase in the neutrino mixing matrix (leptogenesis) and new CP violating interactions involving quarks and gluons at the TeV scale (baryogenesis). The flagship of the US experimental HEP program, the Deep Underground Neutrino Experiment (DUNE) at Fermilab, is designed to probe $\not{C}\not{P}$ in neutrino mixing. For DUNE to reach its design precision (1–2%), one needs to know the ν-^{40}Ar cross-section as a function of 4-momentum transfer with neutrino energy in the range ≈ 300 MeV to ≈ 5 GeV[5;10]. Over this range the contribution of quasi-elastic, resonant, and deep-inelastic scattering are large and vary significantly[9]. These three types of interactions are characterized by the matrix elements (ME) of the electroweak current with a hierarchy of different nuclear components: quarks (q_i), nucleons (N), nucleon plus pion[s], two nucleons ($\langle N|J_{\rm ew}|N\rangle$, $\langle N\pi|J_{\rm ew}|N\rangle$, $\langle N\pi|J_{\rm ew}|N\pi\rangle$, $\langle NN|J_{\rm ew}|NN\rangle$, $\langle q_j|J_{\rm ew}|q_i\rangle$), etc. These ME are incorporated into nuclear models to predict the state of the excited nucleus and its evolution[3]. Such validated nuclear models are essential for the next generation of robust and high fidelity event generators. The goal, therefore, is to calculate these ME using lattice QCD, improve their extraction using phenomenology and global fits, and refine/constrain nuclear models to provide an accurate description of ν-^{40}Ar interactions.

Lattice QCD calculations provide results incorporating all non-perturbative effects, however, one has to demonstrate that all systematic uncertainties due to lattice discretization have been controlled. The best studied quantity using lattice QCD is the one-nucleon ME $\langle N|J_{\rm ew}|N\rangle$. It quantifies the interaction of neutrinos, electrons and muons with nucleons, and is described in terms of four form factors, the electric G_E, magnetic G_M, axial vector G_A and the induced pseudoscalar $\widetilde{G}_P$. Much is known about these. The electric and magnetic have been extracted precisely from electron scattering experiments, $G_E(Q^2=0)=1$ as a result of CVC, $G_M(Q^2=0)=\mu$ the magnetic mopment, $G_A(Q^2=0)=g_A=1.276(2)$ determined from neutron beta-decay, and $g_P^* = \widetilde{G}_P(Q^2 = 0.88m_\mu^2) \approx 0.81$ from muon capture by a proton. The missing pieces are $G_A(Q^2)$ (and $\widetilde{G}_P(Q^2)$ if one does not want to use the pion-pole dominance hypothesis).

The goal of lattice QCD calculations over the next five years is to calculate all the quantities arising in $\langle N|J_{\rm weak}|N\rangle$ with 1–2 percent precision. Comparison with quantities known precisely from experiments will validate the lattice methodology, and $G_A(Q^2)$ and $\widetilde{G}_P(Q^2)$ are the desired predictions. The methodology for these calculations is well-established[6;7]. Precision will improve with higher statistics and reduction of systematic uncertainties, especially in the axial form factors[7]. We project that our ongoing calculations with ten ensembles of 2+1-flavors of Wilson-clover fermions will yield results with the above target precision. A community review of other observables that lattice QCD has calculated with a well quantified error budget has been carried out by the Flavor Lattice Averaging Group (FLAG) Review 2019[1].

Looking further ahead, the lattice methodology for up to two hadrons in the initial and/or final states, $\langle N\pi|J_{\rm ew}|N\rangle$, $\langle N\pi|J_{\rm ew}|N\pi\rangle$ and $\langle NN|J_{\rm ew}|NN\rangle$, has been developed[2;18] and the first calculations to understand and quantify the statistical and systematic uncertainties have been initiated[19]. Knowing these ME will significantly improve the modelling of nuclear effects.

Models of Nuclear Dynamics: The accurate calculation of the electroweak inclusive response of a nucleus is a challenging quantum many-body problem. Its difficulty is compounded by the fact that the energy of the incoming neutrinos is not known (in contrast, for example, to electron scattering where the initial and final electron energies are precisely known). The observed cross section for a given energy and angle of the final lepton results from a folding with the energy distribution of the incoming neutrino flux and, consequently, may include contributions from energy- and momentum- transfer regions of the nuclear response where different mechanisms are at play: the threshold region, where the structure of the low-lying energy spectrum and collective effects are important; the quasi-elastic region, which is (naively, see below) expected to be dominated by scattering from individual nucleons; and the Δ resonance region, where one or more pions are produced in the final state.

Several calculations are based on rather crude models of nuclear structure—Fermi gas or local density approximations of the nuclear matter spectral function—as well as simplistic treatments of the reaction mechanism, and the relevant nuclear matrix elements are often calculated using operators that are not consistent with the underlying Hamiltonian use to describe nuclei.

In the past few years Quantum Monte Carlo calculations have succeeded in accurately describing the nuclear ground- and excited-states, and they have been extended to the calculation of electroweak matrix elements and cross-sections with unprecedented accuracy [3]. The input for these calculations is a many-body Hamiltonian that includes two- and three-body interactions. It describes with high accuracy nucleon scattering data and several properties of nuclei, including energies, radii, distributions and matrix elements [15;17]. Electroweak currents, needed to describe the nuclear interactions with electrons and neutrinos, are derived consistently with the underlying Hamiltonian. Recently, the methods have been extended to calculate electroweak response functions in light nuclei [12;13;16].

In the future, it is of primary importance to combine LQCD calculations of one- and two-nucleon form factors into these many-body calculations, and extend them to medium-mass nuclei, in particular ^{40}Ar.

Deep inelastic region and PDFs: For large $Q \gtrsim 3$ GeV, one can factorize the neutrino-nucleon interaction into a soft and hard part. The hard part, the interaction of a quark with a neutrino with large momentum transfer, can be calculated accurately using electroweak perturbation theory. Progress on the soft part, which describes the properties of quarks and gluons within a nucleon, is proceeding through improvements in phenomenology (global fits and perturbative calculations), experimental data (LHC, JLab, future EIC), and lattice QCD (see the review [11] of the community effort and status of calculations). The goal of this nucleon structure research is to provide the distribution of momentum, helicity, transversity of quarks and gluons as a function of the Bjorken x within a nucleon. These distributions are process independent and global fits incorporate data from lepton scattering and proton colliders to refine them. Main uncertainties in global fit analyses come from the lack of experimental data at small x and the order of perturbative calculations used. Complementing these, Lattice QCD has provided the first moment of the momentum fraction, helicity and transversity with $\approx 10\%$ accuracy. These and higher moment will provide constraints on the PDFs from global fits. Methodology to directly calculate the x-dependence using lattice QCD (such as large momentum effective theory (LaMET) [8]. A review is available [4]) is also being developed and first results are very encouraging.

Neutrino Event Generators: Improvements in the modelling of the excited state of the nucleon and its evolution will be fed into neutrino event generators [14]. These are used to infer the energy of the initial excited nucleus (and thus the incident neutrino energy) from the detected remnants of the struck nucleus. Conversely, knowing the 4-momentum transferred and robust models of the dynamics of the struck nucleus will provide an event-by-event description of the neutrino-nucleus interaction.

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