Snowmass 2021 LoI: Nucleon Form Factors for Neutrino Physics

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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
■ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
□ (NF10) Neutrino detectors
■ (CompF2) Theoretical Calculations and Simulation
■ (TF05) Lattice Gauge Theory

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1. Introduction

In this LOI, we propose LQCD calculations of the nucleon axial form factor and the nucleon-to-delta axial transition form factors to enhance the physics capabilities of the long-baseline neutrino oscillation program currently underway in the US. In particular, matrix elements involving weak interactions, which probe the nucleon axial and pseudoscalar form factors, are impractical to measure experimentally and/or subject to significant model dependence, but are readily accessible to LQCD calculations. Lattice gauge theory techniques permit assignment of comprehensive and robust theoretical uncertainties to computed quantities and results are systematically improvable with only the addition of more compute time.

2. Neutrino Oscillation Physics

Next generation neutrino oscillation experiments necessitate precise neutrino-nucleus cross sections. The neutrino flux energy range spans several different event topologies [1–3], meaning that cross sections on all of these topologies must be understood. The event topologies for the relevant neutrino energy range must be accurate and include controlled, robust uncertainty estimates. Because the neutrino beam is created from decay of pions in flight, the neutrino energy is not known event-by-event and must be reconstructed from a statistical distribution. Studies from deuterium bubble chamber quasielastic neutrino scattering data suggest that uncertainty on axial form factor is underestimated by about an order of magnitude [4]. The dipole form factor parameterization is known to be inconsistent with QCD and only obeys the correct asymptotic behavior in a region beyond the kinematic limits accessible to scattering data [5]. Other studies of electron scattering data also suggest that vector form factors exhibit tension well outside of their quoted uncertainties [6]. This tension must be resolved before a precise axial form factor constraint can be effectively used. Without more robust control of nucleon form factors, it is not possible to determine whether discrepancies between Monte Carlo predictions and experimental data are the result of nucleon level inputs to nuclear models or from the nuclear models themselves.

In both quasielastic scattering [7–9] and pion production interactions [10, 11], data probing axial channel are sparse and do not effectively constrain the form factors. Most of the constraint on the nucleon-to-delta transition form factor comes from assuming a dipole model parameterization and performing global fits to neutrino scattering pion production data over a total of $O(10^2)$ events [12]. Assuming a factor of 3 reduction in uncertainty from restricting to only resonance events and an additional factor of 2 reduction in the uncertainty after correlating the near and far detector event distributions, a 10% normalization uncertainty on the transition form factor would saturate the DUNE theory error budget with a 1.5% target uncertainty [2]. Neutrino charged-current scattering data with a 1π final event topology suggest systematic inconsistencies between the pion and lepton kinematics in comparisons of experiment with Monte Carlo [13].

3. Lattice QCD

LQCD calculations are subject to a set of systematic uncertainties that are disjoint from those of experiments. These systematic uncertainties can be rigorously controlled and reduced using standard LQCD techniques. A key advantage of LQCD calculations is that nucleon form factor calculations are performed on single-nucleon states. The axial form factors are computed directly without the need to appeal to a nuclear model, bypassing many of the complications faced by experimental extractions of the form factors from neutrino scattering data and removing the dependence on model assumptions from other estimates. Some of the main systematics to control for in LQCD calculations are the finite volume, finite lattice spacing, and contamination from excited state contributions. These can be overcome by studying correlation functions on a suite of ensembles with different lattice spacings and physical volumes and by performing calculations with a large basis of interpolating operators. In the absence of a modern neutrino scattering experiment in a deuterium bubble chamber, LQCD is the best technique for extracting nucleon form factor amplitudes without introducing significant model dependence and uncontrollable systematics. The event topologies for the relevant neutrino energy range must be accurate and include controlled, robust uncertainty estimates.

3.1. Quasielastic Scattering

Computations of the nucleon axial form factor and axial charge with applications in quasielastic scattering are well underway at present. For a recent literature review, see Ref. [14]. Several results are published with full control of all systematic uncertainties at zero momentum transfer, and some including form factor Q^2-dependence of the target nucleon. In the past, LQCD computations of the axial charge $g_A = F_A(Q^2 = 0)$ have been low by $10 - 15\%$ [15]. The cause of this discrepancy has been the subject of some controversy [16–19]. The most recent calculations [20–27] reduced the statistical errors, some to about a percent, and appear to be closer to the experiment. The new calculations in the next decade will address effects that have been conventionally neglected such as isospin breaking and unquenched charm.

In the next decade, additional computing resources will permit precision calculations of the axial form factor capable of reaching percent-level precision over a range of Q^2 rather than at only $Q^2 = 0$. Computations at several momentum transfers on several ensembles will enable an extraction of the axial form factor with full control over systematics effects. These data will be fit to a model-independent z expansion, which is a small-parameter expansion with rapid convergence [5]. The large-Q^2 behavior beyond the kinematically-accessible region can be controlled, up to logarithmic corrections, with a set of sum rules on higher-order expansion coefficients.

3.2. Resonance Scattering - $N \to \Delta$ Transition

The nucleon-to-delta transition form factor is more difficult to compute with LQCD. The finite volume mixes states with the same quantum numbers yielding finite-volume states that are linear combinations of infinite-volume asymptotic states. Resonances result in additional states that appear in finite volume. Mixing can be substantial for multiparticle states with other multiparticle or resonance states, with power-law corrections to masses and matrix elements. This is well-understood in the case of two-particle states, where the Lüscher quantization condition is used to relate the energy spectrum to the scattering matrix elements. There is active research to work out relations for matrix elements with three-particle states, which is nearly complete.

An earlier approach computed the transition form factor at unphysical pion mass [28], where the Delta baryon is stable and an extrapolation to physical mass may be performed. A modern update of this calculation using derivative methods in Ref. [29] could yield an order-of-magnitude estimate of the value and slope with respect to 3-momentum transfer of the nucleon to delta transition matrix element. This is enough to check consistency with deuterium bubble chamber neutrino scattering data in the $CC1\pi$ channel and can give valuable information about the normalization of the axial transition form factor.

In the limit of physical pion mass, where the delta baryon becomes unstable, the computation becomes significantly more complicated due to a low-lying $N\pi\pi$ state with all three particles at rest. This three-particle state has slightly lower mass than the unstable delta baryon and could mix significantly with the finite-volume resonance state. The lowest $N\pi$ state must be in a P-wave to satisfy parity symmetry, so the nucleon and pion in the state must have back-to-back momenta at the lowest allowable quantized lattice momentum. The energy of this state assumed from the dispersion relation is about 1.35GeV for ensembles with $L \sim 6.0$fm, which is larger than the at-rest $N\pi\pi$ state with a mass of about 1.21GeV. This computation may still be tackled with a modest operator basis including an N, $N\pi$, and $N\pi\pi$ interpolating operator, although the Wick contraction combinations for these operators are complicated.

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