Lattice-QCD Calculations Supporting Neutrino-Oscillation Experiments

Fermilab Lattice and MILC Collaborations

August 31, 2020

NF Topical Groups:

- ☐ (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

Other Topical Groups:

- ■ (CompF2) Theoretical Calculations and Simulation
- ■ (TF05) Lattice Gauge Theory

Contact Information:
Andreas S. Kronfeld (Theoretical Physics Department, Fermilab) [email]: ask@fnal.gov

Authors:
A. Bazavov, C. DeTar, A.X. El-Khadra, E. Gámiz, Z. Gelzer, Steven Gottlieb, U.M. Heller, R.J. Hill, C. Hughes, W.I. Jay, A.S. Kronfeld, S. Lahert, J. Laiho, Yin Lin (林胤) P.B. Mackenzie, A.S. Meyer, E.T. Neil, J. Osborn, J.N. Simone, A. Strelchenko, R.L. Sugar, D. Toussaint, R.S. Van de Water, A. Vaquero Avilés-Casco

Lattice-QCD Calculations Supporting Neutrino-Oscillation Experiments

A central part of the U.S. high-energy physics program is the investigation of neutrino masses and mixing angles, including related issues such as the number of sterile neutrino species. The basic technique is to measure flux-integrated cross-section measurements at near and far detectors and infer the mass splittings and mixing angles from a comparison of the shapes of the near and far detector spectra. In these experiments, a neutrino beam impinges on an active target consisting of nuclei such as ^{12}C, ^{16}O, or ^{40}Ar. In a scattering event, the incident neutrino energy-momentum is not known and, thus, must be inferred from measurements of the final state. Unfortunately, not all remnants of the collision are detected, leading inevitably to some dependence of the reconstructed energy on modeling the neutrino-nucleus interactions.

These interactions are not very well understood, and a major focus of the high-energy and nuclear physics communities in the coming decade will be to improve this understanding. There are several strategies. The DUNE experiment, for example, aims to carry out enough detailed measurements to mitigate their reliance on nuclear modeling. Even so, it seems likely that improvements in the modeling will strengthen DUNE's scientific results. As outlined in a 2019 whitepaper by the USQCD Collaboration [1], several lattice-QCD calculations of nucleon matrix elements can be used with a nuclear effective field theory of pions and nucleons (and, perhaps, other hadrons) in the context of nuclear many-body theory. As discussed in another LOI [2], several nuclear theorists and lattice-QCD practitioners are interested in developing this idea into a real framework.

In this Letter of Interest, we discuss what we (the Fermilab Lattice and MILC Collaborations) intend to pursue with lattice QCD. The DUNE/LBNF neutrino beam has significant flux in the energy region $1\ \text{GeV} \lesssim E_\nu \lesssim 6\ \text{GeV}$. In this range, several qualitatively different processes take place. In increasing energy: quasielastic scattering, nucleon-to-resonance transitions, "shallow" inelastic scattering, and deep inelastic scattering. By "shallow" inelastic scattering, we mean that the event has too many pions to be understood via resonances, but too little energy for the operator-product expansion to allow factorization (see below).

Relevant lattice-QCD calculations are, in order, *nucleon form factors* for the quasielastic region (especially the axial form factor); *nucleon-to-resonance form factors* in the resonance region (for example, $\nu_\ell N \to \ell\Delta$); the *nucleon hadron tensor* in the shallow inelastic region; and *parton distribution functions* (PDFs) in the deep inelastic region.

We have begun a calculation of the axial form factor with resources from USQCD and from the DOE ALCC program. This work builds on our extensive experience with B-, D-, and K-meson form factors, particularly the careful examination and quantification of systematic uncertainties. In the context of the anomalous magnetic moment of the muon [3], we are developing the expertise and software infrastructure to study multi-hadron final states and their connection to resonances. We also have a pilot project on the hadron tensor of the pion, which is a learning experience anticipating a calculation of the nucleon hadron tensor. In other projects, we are developing codes and experience for multi-hadron final states. The Δ-baryon form factors require, in principle, a complete description of the $\Delta \leftrightarrow N\pi$ resonance, which is amenable to lattice-QCD calculations. At this time, we are *not* planning a campaign of PDF calculations, but many other lattice-QCD groups are engaged in this activity. Note that the HISQ ensembles are publicly available for other groups to use for PDF calculations.

Multi-hadron final states push the limit of current-day lattice-QCD calculations, but will be an important frontier in the coming decade. In other work, we plan to address the $B \to K^*\ell\ell$ transition [4], which will aid us in understanding multi-hadron final states. Many of the conceptual issues in this decay will inform our calculations of $N \to \Delta$ form factor. The key point is that the K^* is a $K\pi$ resonance, and the Δ is a $N\pi$ resonance.

In the work envisioned here, we plan to employ the large set of lattice-gauge-field ensembles—known as the "HISQ" ensembles—generated over the past decade by the MILC Collaboration [5, 6]. These ensembles have the widest available range of lattice spacing, uniformly high statistics, and physical light-quark masses in the sea (as well as slightly heavier light sea quarks, corresponding to pion masses of (approximately) 220 and 310 MeV). There are around two dozen ensembles: combining data from them into a single analysis has led to unprecedented sub-percent uncertainties for the simplest quantities (decay constants for leptonic decays of mesons [6] and quark masses [7]). The HISQ ensembles are a unique resource for particle and nuclear physics.

The understanding of neutrino-nucleus interactions can also be furthered by directly studying nuclei in lattice QCD. This is an active area of research in the lattice-QCD community, but one in which we are not ourselves active. In the near term, these studies will be restricted to nuclei smaller than those in the targets used in oscillation experiments. Nevertheless, these calculations can be used to test the chiral effective field theory, extending the tests of $N \to \Delta \leftrightarrow N\pi$ transitions mentioned above.

References

[1] A. S. Kronfeld, D. G. Richards, W. Detmold, R. Gupta, H.-W. Lin, K.-F. Liu, A. S. Meyer, R. Sufian, and S. Syritsyn (USQCD), Eur. Phys. J. A **55**, 196 (2019), arXiv:1904.09931 [hep-lat] .

[2] N. Rocco, M. Wagman, *et al.*, (2020), NF/SNOWMASS21-NF6_NF0-TF11_TF5-CompF2_CompF0_Michael_Wagman-177.pdf.

[3] A. El-Khadra *et al.* (Fermilab Lattice, MILC), (2020), RF/SNOWMASS21-RF3_RF0-EF5_EF0-TF5_TF0-CompF2_CompF0_El-Khadra-103.pdf.

[4] C. DeTar *et al.* (Fermilab Lattice, MILC), (2020), RF/SNOWMASS21-RF1_RF0-EF5_EF0-TF5_TF0-CompF2_CompF0_DeTar-047.pdf.

[5] A. Bazavov *et al.* (MILC), Phys. Rev. D **87**, 054505 (2013), arXiv:1212.4768 [hep-lat] .

[6] A. Bazavov *et al.* (Fermilab Lattice, MILC), Phys. Rev. D **98**, 074512 (2018), arXiv:1712.09262 [hep-lat] .

[7] A. Bazavov *et al.* (Fermilab Lattice, MILC, TUMQCD), Phys. Rev. **D98**, 054517 (2018), arXiv:1802.04248 [hep-lat] .