Neutrino-Nucleus Scattering Brief

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The precision era of ν physics

Next-generation oscillation experiments can answer fundamental questions about the neutrino mass ordering, size of leptonic CP violation, and more

Discovering new physics with ν experiments requires control of all the Standard Model physics in the detector

Acciarri et al (DUNE) arXiv 1512.06148

$$N_{\text{FD}}^{\text{expected}}(\nu_e) = N_{\text{ND}}^{\text{data}}(\nu_\mu) \otimes \frac{\Phi_{\text{FD}}(\nu_\mu)}{\Phi_{\text{ND}}(\nu_\mu)} \otimes P(\nu_\mu \rightarrow \nu_e) \otimes \frac{\varepsilon_{\text{FD}}(\nu_e)}{\varepsilon_{\text{ND}}(\nu_\mu)} \otimes \frac{\sigma_{\text{FD}}(\nu_e)}{\sigma_{\text{ND}}(\nu_\mu)}$$

Measured
Goal
 νA cross-section

Exclusive νA cross-sections required for event-by-event reconstruction of incident neutrino energy

Challenges of νA

Neutrino-argon cross-sections with few percent-level accuracy required to achieve design sensitivity to CP violation at DUNE

Acciarri et al (DUNE) arXiv 1512.06148

Accelerator neutrino flux covers a wide range of energies with different dominant physics processes:

- Quasi-elastic
- Resonance production
- Transition region
- Deep inelastic scattering

Event Generators for Accelerator-Based Neutrino Experiments

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Incorporating all constraints on νA from experiment and LQCD in neutrino Monte Carlo event generators is critical

Factorization of leptonic and hadronic parts allows easier verification of nuclear models (e.g. vs electron scattering, where generator progress is still needed) and searches for novel new physics signatures

A coordinated framework of modular event generator components would simplify comparing and understanding systematic uncertainties of generators

Ankowski, Friedland PRD 102 (2020)

Lattice QCD and νA

LQCD can provide accurate constraints on νA scattering across energies

See USQCD νA white paper: Kronfeld et al Eur. Phys. J. A 55 (2019)

Lattice QCD and νA

Snowmass 2021 LoI: Nucleon Form Factors for Neutrino Physics

Taku Izubuchi,^{a,b} Christoph Lehner,^{a,c} Aaron S. Meyer,^{a,*} Shigemi Ohta^{b,d,e}, Sergey Syritsyn^{b,f}

Lattice-QCD Calculations Supporting Neutrino-Oscillation Experiments

Fermilab Lattice and MILC Collaborations

Theoretical predictions of Neutrino-nucleus Interactions

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Lattice Calculation of Neutrino-Nucleon Cross Section

Keh-Fei Liu¹ (liu@g.uky.edu), Terrence Draper¹, Jian Liang¹, G. Wang¹, Yi-Bo Yang², and Yong Zhao³

Connecting QCD to neutrino-nucleus scattering

Joseph Carlson¹, Chia Cheng Chang (張家丞)^{2,3,4}, William Detmold⁵, Joshua Isaacson⁶, William Jay⁶, Gurtej Kanwar⁵, Andreas Kronfeld⁶, Huey-Wen Lin⁷, Yin Lin (林胤)^{6,8}, Keh-Fei Liu⁹, Alessandro Lovato^{10,11}, Pedro Machado⁶, Aaron S. Meyer¹², Saori Pastore¹³, Noemi Rocco^{6,10}, Phiala Shanahan⁵, and Michael Wagman⁶

Nucleon form factors

νA scattering amplitudes factorize into leptonic and hadronic parts

$$\mathcal{M}_{\nu A \rightarrow \ell f} \propto \left[\bar{u}_\ell \gamma_\mu \left(\frac{1 - \gamma_5}{2} \right) u_\nu \right] \langle f | \bar{q} \gamma_\mu \left(\frac{1 - \gamma_5}{2} \right) q | A \rangle$$

Single-nucleon currents dominate at low energies where nucleons are effective degrees of freedom for nuclei, multi-nucleon currents provide corrections

Nucleon vector and axial form factors are key inputs to nuclear EFTs / models

$$\langle N(p') | A_\mu(q) | N(p) \rangle = \bar{u}(p') \left[G_A(Q^2) \gamma_\mu \gamma_5 + \frac{\tilde{G}_P(Q^2)}{2M_N} q_\mu \gamma_5 \right] u(p)$$

Vector form factors measured in electron scattering, axial form factors less constrained

Nucleon form factors

Calculations of vector current form factors performed at physical quark masses:

Recent axial form factors studies demonstrated the importance of $N\pi$ excited-state effects in achieving controlled systematic uncertainties

Nucleon form factors

Neutrino Scattering Measurements on Hydrogen and Deuterium

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Nucleon form factors also directly accessible without nuclear uncertainties in experiments using elementary targets

Neutrino scattering with hydrogen and deuterium provides clean environment for measuring nucleon form factors and simplest nuclear effects

Options include solid H target (straw tube tracker), liquid- H_2/D_2 bubble chamber, and high-pressure gas TPC (H mixture, He, ...) at DUNE near detector

Baltay et al. Reflections on the 15-Foot Bubble Chamber at Fermilab (1988)

Hadron tensor

Lattice Calculation of Neutrino-Nucleon Cross Section

Keh-Fei Liu¹ (liu@g.uky.edu), Terrence Draper¹, Jian Liang¹, G. Wang¹, Yi-Bo Yang², and Yong Zhao³

Neutrino nucleus cross-section factorizes into product of lepton and hadron tensors

$$W_{\mu\nu}(q^2, \nu) = \int \frac{d^4x}{4\pi} e^{iq \cdot x} \langle N(p') | J_\mu(x) J_\nu(0) | N(p) \rangle$$

$$= \int \frac{d^4x}{4\pi} e^{iq \cdot x} \sum_f \langle N(p') | J_\mu(x) | f \rangle \langle f | J_\nu(0) | N(p) \rangle$$

Hadron tensor calculations require inverse Laplace transform of LQCD 4pt functions, exploratory calculations underway using Backus-Gilbert, maximum entropy, Bayesian reconstruction

Below inelastic thresholds, nucleon hadron tensor equal to square of elastic form factors

Above inelastic thresholds, nucleon hadron tensor accesses sum over all intermediate states and could inform nuclear models of resonance, transition, and DIS regions

Resonance production

π production essential for reproducing cross-section at energies above quasi-elastic region

Exclusive π production amplitudes important for neutrino Monte Carlo event generators

Rocco, Nakamura, Lee, Lovato, PRC 100 (2019)

Δ resonance contributions important and poorly known ingredient to nuclear models of resonance region

Exploratory LQCD calculations of N , π , Δ performed at heavy quark masses where Δ stable

Leinweber, Draper, Woloshyn PRD 48 (1993)

...

Alexandrou et al, PRD 77 (2008)

Fully controlled LQCD calculations at physical point require sophisticated finite-volume formalism and numerical techniques for $N\pi$ scattering states

Two-body currents

Two-body current effects are essential for reproducing νA scattering data in shallow inelastic region

Rocco, Nakamura, Lee, Lovato, PRC 100 (2019)

$A=30-50$ nuclei have $O(30\%)$ smaller axial couplings than predicted by shell model with single-particle couplings

Multi-nucleon correlations and currents needed to reproduce β -decay results from experiment

Gysbers et al, Nature Phys. 15 (2019)

Two-body currents

Constraints on two-body axial currents obtained by matching LQCD and EFT calculations in a box with a background axial field

$$iC_{pp \rightarrow np(^3S_1)} = \text{[Feynman diagram: loop with wavy line]} + \text{[Feynman diagram: contact]} + \dots$$

$$\mathcal{M}_{pp \rightarrow np(^3S_1)} = gA(1 + S) - L_{1A}$$

Short-distance QCD physics

Used for exploratory LQCD determination of L_{1A} [Savage et al \[NPLQCD\], PRL 119 \(2017\)](#)

LQCD calculations of $A = 2-3$ matrix elements sensitive to two-body currents performed at unphysically heavy quark masses

Further study of NN excited states needed to understand discrepancies between these calculations and recent results using different interpolating operators:

[Francis et al, PRD 99 \(2019\)](#)

[Hörz et al, arXiv:2009.11825](#)

Nucleon / nuclear PDFs

At very high energies, cross-sections factorize into convolutions of perturbative quark-and-gluon-level amplitudes and nonperturbative PDFs

Some aspects of PDFs are experimentally well-known, but others (e.g. flavor dependence, nuclear effects) are not

LQCD constraints can improve global analyses of isovector polarized PDFs

Bringewatt et al [JAM], arXiv:2010.00548

LQCD constraints can also improve global analyses of nuclear PDFs

Detmold et al [NPLQCD], arXiv:2009.05522

Conclusions

Describing νA scattering from the Standard Model requires control of QCD over a wide range of scales and physics processes

Challenging but possible through lattice QCD + nuclear many body methods

Nucleon form factors
Hadron tensor
Resonance production
Two-body currents
PDF constraints

Nuclear EFTs
Spectral functions
Nuclear PDFs

Event generators