Snowmass2021 - Letter of Interest

Microscopic approaches to neutrino-nucleus interactions

NF Topical Groups: (check all that apply ☐/■)

■ (NF6) Neutrino cross sections
■ (TF11) Theory of Neutrino Physics
■ (CompF2) Theoretical Calculations and Simulation

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Abstract

Precise theoretical calculations of neutrino scattering cross sections on target nuclei are essential to the success of the experimental program at short- and long-baseline neutrino oscillation facilities. These calculations require a quantitative understanding of all the reaction mechanisms, including single-nucleon interactions and many-body nuclear dynamics, that are at play in the broad range of energies and momenta relevant to oscillation experiments. One of the major goals is to quantify the impact of nuclear and hadronic uncertainties on the extraction of neutrino oscillation parameters. With this LOI we highlight the importance of microscopic calculations of lepton-nucleus cross sections and motivate the work to be undertaken in the near and long future.

Motivation

Nuclear physics, and, in particular, theoretical neutrino-nucleus cross sections are a fundamental prerequisite for the correct interpretation of the wealth of data taken from existing and planned neutrino-oscillation experiments. Neutrino-oscillation parameters are extracted from the energy distribution of the oscillated flux, which has to be reconstructed from the final hadronic states observed in the detector and, in the case of charged-current transitions, from the kinematics of the outgoing lepton. To this aim, neutrino experiments rely on simulations carried out by neutrino event generators, such as GENIE[1], NuWro[2], and GiBUU[3], which in turn use as inputs theoretical calculations of neutrino-nucleus cross sections. Therefore, the success of the experimental program relies on *i*) a theoretical control of neutrino interactions with nucleons and nuclei, and *ii*) the prompt implementation of sophisticated nuclear models into neutrino event generators.

Several microscopic approaches to the nuclear many-body problem[4–6], in which the fundamental degrees of freedom are protons and neutrons and nuclear properties emerges form their individual interactions, clearly demonstrated that multi-nucleon correlations and currents are needed to quantitatively reproduce available electron-scattering experimental data. Quantum Monte Carlo (QMC) methods, and more specifically the variational Monte Carlo (VMC) and Green's function Monte Carlo (GFMC) approaches, allow one to fully retain the complexity of many-body correlations and associated electroweak currents. They have been extensively applied to study the structure and electroweak properties of light nuclei, including electromagnetic moments and form factors, low-energy transitions and beta decays[7]. The GFMC has also been employed to perform *virtually exact* calculations of inclusive electron- and neutrino-scattering[8–10] on ^{4}He and ^{12}C, which turned out to be in excellent agreement with experiments in the quasi-elastic region.

Since its computational cost grows exponentially with the number of nucleons, the GFMC will be limited to light nuclei, with $A \lesssim 14$ even when Exascale computers become available. As an additional limitation, within the GFMC it is difficult to compute inelastic scattering, and include fully-relativistic kinematics and currents. Alternative methods based on the factorization of the final hadronic state, such as those relying on the spectral function (SF) of the nucleus[11;12] and the short-time approximation (STA)[13] are suitable to study larger nuclear systems relevant to the experimental program, while retaining most of the important effects coming from multi-nucleon physics. These methods can accommodate fully-relativistic kinematic and currents, as well as pion production mechanisms — as already demonstrated within the SF formalism[14]. They also provide detailed information on the kinematic variables associated with the hadronic final states. As an example, the ^{4}He response density induced by electrons computed with the STA is displayed in Fig. 1 as a function of the center of mass and relative energies of the struck pair of nucleons. The densities retain the information at the interaction vertex with the external probe.

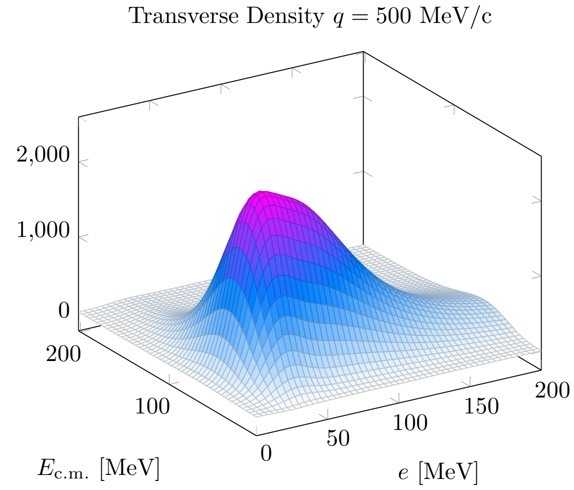

Figure 1: Electromagnetic transverse response density for ^{4}He in terms of the center of mass ($E_{\mathrm{c.m}}$) and relative (e) energies of the struck pair of nucleons for momentum transfer $q = 500\,\mathrm{MeV/c}$.

Outlook

In the forthcoming years, we expect to develop and consolidate a set of consistent microscopic algorithms that are suitable to perform accurate calculations of neutrino-nucleus cross sections on nuclei and energy regimes of experimental interest. Below a list of planned goals:

- Extend virtually-exact QMC calculations to the inclusive nuclear response functions relevant for neutrino scattering on ^{16}O and ^{40}Ar in the quasi-elastic region. Validate the approach against the large body of electron-scattering data[15]. Requirements: algorithmic development; availability of high-performance computing resources.
- Perform QMC calculations of quasi-elastic lepton-nucleus scattering and muon-capture rates using nuclear correlations and electroweak currents consistently derived within effective field theory frameworks. Utilize inputs from lattice-QCD[16] to describe nucleons' properties and couplings to further constrain two-body dynamics. Determine the theoretical uncertainties associated with the calculations and validate theoretical predictions with available experimental data on different nuclei.
- Perform thorough comparisons among QMC, SF, and STA approaches to precisely quantify the uncertainties inherent to the factorization of the final state. Determine the importance of relativistic effects in both the interaction vertex and in the kinematics of the reaction in the whole energy region relevant for oscillation experiments.
- Use the STA and the SF methods to attain information on the hadronic final states and on the response densities to tackle exclusive processes – including resonance and pion-production – that will be measured by the next generation detectors that use liquid-argon technology.
- Implement the QMC, SF, and STA results in commonly used event generators. Perform extensive validation with electron scattering data, in a collaborative effort with dedicated experimental programs[15;17;18], and use the attained information to accurately study neutrino-scattering and precisely compare with experiments.

References

[1] C. Andreopoulos et al. The GENIE Neutrino Monte Carlo Generator. *Nucl. Instrum. Meth. A*, 614:87–104, 2010.

[2] Tomasz Golan, Cezary Juszczak, and Jan T. Sobczyk. Final State Interactions Effects in Neutrino-Nucleus Interactions. *Phys. Rev.*, C86:015505, 2012.

[3] Ulrich Mosel. Neutrino event generators: foundation, status and future. *J. Phys. G*, 46(11):113001, 2019.

[4] J. Carlson, S. Gandolfi, F. Pederiva, Steven C. Pieper, R. Schiavilla, K. E. Schmidt, and R. B. Wiringa. Quantum Monte Carlo methods for nuclear physics. *Rev. Mod. Phys.*, 87:1067, 2015.

[5] Sonia Bacca and Saori Pastore. Electromagnetic reactions on light nuclei. *J. Phys.*, G41(12):123002, 2014.

[6] A. Lovato, S. Gandolfi, J. Carlson, Steven C. Pieper, and R. Schiavilla. Electromagnetic response of ^{12}C: A first-principles calculation. *Phys. Rev. Lett.*, 117(8):082501, 2016.

[7] G.B. King, L. Andreoli, S. Pastore, M. Piarulli, R. Schiavilla, R.B. Wiringa, J. Carlson, and S. Gandolfi. Chiral Effective Field Theory Calculations of Weak Transitions in Light Nuclei. *Phys. Rev. C*, 102(2):025501, 2020.

[8] A. Lovato, S. Gandolfi, R. Butler, J. Carlson, E. Lusk, S. C. Pieper, and R. Schiavilla. Charge form factor and sum rules of electromagnetic response functions in ^{12}C. *Phys. Rev. Lett.*, 111:092501, 2013.

[9] Noemi Rocco, Winfried Leidemann, Alessandro Lovato, and Giuseppina Orlandini. Relativistic effects in ab-initio electron-nucleus scattering. *Phys. Rev. C*, 97(5):055501, 2018.

[10] A. Lovato, J. Carlson, S. Gandolfi, N. Rocco, and R. Schiavilla. Ab initio study of (ν_ℓ, ℓ^-) and $(\overline{\nu}_\ell, \ell^+)$ inclusive scattering in ^{12}C: confronting the MiniBooNE and T2K CCQE data. 3 2020.

[11] N. Rocco, L. Alvarez-Ruso, A. Lovato, and J. Nieves. Electromagnetic scaling functions within the Green's Function Monte Carlo approach. *Phys. Rev. C*, 96(1):015504, 2017.

[12] Noemi Rocco. Ab initio calculations of lepton-nucleus scattering. *Frontiers in Physics*, 8:116, 2020.

[13] Saori Pastore, Joseph Carlson, Stefano Gandolfi, Rocco Schiavilla, and Robert B. Wiringa. Quasielastic lepton scattering and back-to-back nucleons in the short-time approximation. *Phys. Rev. C*, 101(4):044612, 2020.

[14] Noemi Rocco, Satoshi X. Nakamura, T.S.H. Lee, and Alessandro Lovato. Electroweak Pion-Production on Nuclei within the Extended Factorization Scheme. *Phys. Rev. C*, 100(4):045503, 2019.

[15] J. Barrow, S. Gardiner *et al.*, Quasielastic Electromagnetic Scattering Cross Sections and World Data Comparisons in the `GENIE` Monte Carlo Event Generator, in preparation (2020).

[16] Yong-Chull Jang, Rajan Gupta, Boram Yoon, and Tanmoy Bhattacharya. Axial Vector Form Factors from Lattice QCD that Satisfy the PCAC Relation. *Phys. Rev. Lett.*, 124(7):072002, 2020.

[17] R. Cruz-Torres et al. Probing Few-Body Nuclear Dynamics via ^{3}H and ^{3}He $(e, e'p)$pn Cross-Section Measurements. *Phys. Rev. Lett.*, 124(21):212501, 2020.

[18] H. Dai et al. First measurement of the Ar$(e, e')X$ cross section at Jefferson Laboratory. *Phys. Rev. C*, 99(5):054608, 2019.