Snowmass2021 - Letter of Interest

Neutrino Scattering Measurements on Hydrogen and Deuterium

NF and related Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
■ (NF8) Theory of neutrino physics
■ (NF10) Neutrino detectors
■ (TF05) Lattice Gauge Theory
■ (TF11) Theory of neutrino physics
■ (RF6) Dark sector studies at high intensities

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Abstract:

Neutrino interaction uncertainties are a limiting factor in current and next generation experiments probing the fundamental physics of neutrinos, a unique window on physics beyond the Standard Model. Neutrino-nucleon scattering amplitudes are an important part of the neutrino interaction program. However, since all modern neutrino detectors are composed primarily of heavy nuclei, knowledge of elementary neutrino-nucleon amplitudes relies heavily on experiments from an earlier age whose statistical and systematic precision are insufficient for current needs. We are preparing a white paper in which we outline the motivation for measurements on hydrogen and/or deuterium that would improve this knowledge, and discuss options for making these measurements either at the DUNE near detector or at a dedicated facility. This Letter of Intent briefly summarizes the planned white paper.

Motivation:

Current and next generation accelerator-based neutrino experiments are poised to answer fundamental questions about neutrinos. Precise neutrino scattering cross sections on target nuclei are critical to the success of these experiments[1]. These cross sections are computed using nucleon-level amplitudes combined with nuclear models. Regardless of whether nuclear corrections are constrained experimentally or derived from first principles, independent knowledge of the elementary nucleon-level amplitudes is essential.

A rich set of fundamental Standard Model processes are accessed using neutrino-nucleon scattering, ranging from quasielastic scattering (including QED radiation), production of single and multiple pions as well as hadrons with strangeness, hard photon emission, and total inclusive cross sections mediated by the charged- and neutral-current weak interactions. The kinematic region where the transition from the baryon-resonance dominated to the deep-inelastic scattering regime takes place is poorly known. The conjecture of quark-hadron duality on one hand and higher-twist corrections on the other are valuable tools to achieve a consistent description, but progress in their development is hindered by the lack of experimental nuclear-effect-free information from elementary targets[2]. All these processes are relevant for the future of neutrino oscillation measurements and proton-decay searches. In particular, their precise measurement would provide priceless input for the event generators used in oscillation analysis, helping to reduce systematic uncertainties. They are also interesting by themselves as a source of currently unknown information about the axial structure of hadrons, since they directly impact CKM unitarity tests, nucleon axial radius determinations, study of nucleon-to-resonance axial transitions, and provide important inputs and targets for theoretical methods such as lattice QCD[3], and experimental measurements using muon capture[4;5], parity violating electron scattering[6;7] or meson electroproduction[8–20]. Polarization asymmetries can probe the axial form factor complementary to unpolarized measurements and enable the first extraction of the pseudoscalar proton form factor from neutrino data without assumptions regarding its form[21]. Improved precision on the CKM unitarity tests will have an immediate impact on the interpretation of BSM physics contributions[22].

In addition to improving on longstanding issues with neutrino-nucleon interactions, a dedicated elementary target in the LBNF beamline can also serve as a facility with which to search for new physics[23–26]. A fiducial mass of $O(1\text{ t})$ is roughly an order of magnitude smaller than the liquid argon DUNE near detector fiducial mass[27], but it will be advantageously composed of elementary nuclei rather than ^{40}Ar. Thus, even modest [i.e. $O(10-100)$] increases in the cross section per nucleon in hydrogen relative to argon (for instance due to a lack of Pauli-blocking, isospin selection rules, or simple kinematic considerations) will lead to event rates that are comparable to the DUNE near detector. Better yet, systematic uncertainties and model dependence due to nuclear physics are eliminated (for ^{1}H) or drastically reduced (for ^{2}H), and there are clear prospects in, for example, a bubble chamber-like apparatus to lower proton recoil thresholds. This would allow searches for hadrophilic or leptophobic new physics that naturally leads to proton recoils with energies of a few to tens of MeV. Such low recoils may be challenging to realize from a high energy beam, but could arise from sequential decays within an interacting dark sector. This subject deserves further study, but would allow the community to further leverage the high intensity LBNF beamline which has already been recognized as an ideal "dark sector factory"[23–26]. Finally, in a broader context, even for processes whose cross section per nucleon is roughly constant between ^{40}Ar and ^{1}H, an elementary target would provide an independent verification of any hadrophilic signal seen in the DUNE near detector. Such a verification would substantially increase the new-physics discovery potential of the LBNF facility as a whole and provide a cross-check with independent systematic uncertainties that are free from complications due to nuclear physics.

Experimental Options:

In order to meet these goals, we are considering several alternative experimental approaches, each with its advantages and challenges. A possible approach is offered by instrumenting the SAND near detector[28] in DUNE with a straw tube tracker (STT). This design integrates thin layers – 1-2% of a radiation length – of various passive materials between layers of straw tubes of negligible mass. This technology allows the implementation of a "solid" hydrogen target, obtained by subtracting measurements on dedicated graphite (pure C) and polypropylene (CH_2) targets after a kinematic selection enhancing the purity of the H samples to 80-95%, depending on the specific process considered[29–32]. The graphite targets provide a model-independent subtraction of the residual background from interactions on carbon, thus reducing systematic uncertainties. All exclusive and inclusive processes in ν and $\bar{\nu}$ CC interactions on H can be selected, but this technique is limited to hydrogen. Deuterated hydrocarbon polymers are available commercially but only in small quantities and they are very expensive.

Another approach under consideration is to fill the high-pressure gas TPC proposed as part of the DUNE near detector complex with different gases containing hydrogen and/or deuterium. Pure hydrogen or deuterium is not permitted by safety requirements, but hydrogen-containing compounds mixed with argon or other inert gases could be viable. The same transverse-kinematic analysis technique proposed above for use in a solid hydrocarbon target may be used in gas as well[33]. Helium may also be a viable target component if elementary amplitudes can be extracted more reliably from it than from heavier nuclei. A room-temperature liquid time projection chamber has attractive properties. Tetramethylsilane is rich in hydrogen, liquid at room temperature, and it allows electrons to drift[34]. Other compounds may prove to be even more advantageous.

We are also considering a dedicated on-axis facility in a separate underground hall upstream of the proposed DUNE near-detector hall. A liquid-H_2/D_2 bubble chamber appears to be the most attractive option for an active target that maximizes target mass and minimizes volume. Personnel would not be allowed underground while hydrogen or deuterium is in the apparatus, complicating operations and maintenance. It may be advantageous to fill the hall with an inert gas such as nitrogen to improve fire safety. Electrons drift very slowly in liquid hydrogen, and so a liquid hydrogen time projection chamber relying on collecting the drifting charge would not work, if only because the required electron lifetime for capture on impurities would be very difficult to achieve, and because several spills' worth of data would be present on every readout. A magnetized optical bubble chamber may be the best technology. Modern digital camera technology and computerized reconstruction techniques can provide improvements over older bubble chambers. The existing 15' bubble chamber at Fermilab can provide an example or even re-usable parts[35]. Auxiliary detectors to identify muons and electrons will be required for a complete suite of measurements, due to the long radiation and interaction lengths in liquid hydrogen.

Spin-polarized targets allow measurements of cross section asymmetries that have never been directly measured before, and which provide an independent means of ascertaining the proton axial structure. Dynamic nuclear polarization (DNP) has been used[36] in fixed-target experiments with charged-particle beams using targets composed of NH_3 (e.g., SMC[37] and SpinQuest[38]), LiH (e.g., COMPASS[39]), and butanol (e.g., SMC and the FroST target[40] at JLAB). The technique requires a strong magnetic field (2.5 to 5 T magnets have been used), and temperatures ranging from 30 mK to 1 K. We will explore ways to scale this technology up to a size that would work as a neutrino interaction target with integrated particle detection. An integrated target and detector would be needed, as the target material is solid and some particles may stop in it. Sandwiches of detector and target material may be needed to accomplish the goals of the experiment. Experiments at JLab have been able to measure the spin states of protons recoiling from electron-nucleus scattering experiments[41]. If a proton polarimeter could be devised that can work in concert with a large neutrino target, previously-unmeasured asymmetries in neutrino-nucleus scattering would be available for constraining nucleon structure and BSM physics.

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