Neutrino scattering and nuclear structure

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Neutrino-nucleus interactions play a pivotal role in several domains at the forefront of new physics developments, including oscillation experiments, astrophysical neutrino investigations and beyond-standard-model searches. A thorough understanding of the nuclear physics processes involved is therefore crucial. Both experimental and theoretical developments are needed to achieve this goal. In this contribution, we present the current status, opportunities and *challenges* of neutrino-nucleus scattering programs at various energy scales.

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I. CONTEXT

The electroweak sector of the Standard Model has been both puzzling and inspiring physicists for decades. On the one hand, many fundamental questions about neutrino properties still remain unanswered, such as absolute masses, their ordering and the CP violating phase. On the other, neutrinos have the potential to carry information about astrophysical sources as e.g. supernova bursts, or expand our understanding of nuclear structure thanks to their sensitivity to the neutron distribution of nuclear systems. Recently, experiments involving neutrinos, for a broad range of energy scales and for many nuclear systems, started gaining more momentum. As the field enters the precision era, in many endeavors the interplay between particle and nuclear physics becomes even more important. This concerns both our understanding of standard neutrino-nucleus interactions and of Beyond Standard Model (BSM) searches. Among many research directions, we would like to draw attention to several programs: neutrino oscillation experiments, detection of supernova neutrinos, and coherent elastic neutrino-nucleus measurements. In all cases, the role of nuclear physics is predominant and theoretical developments are urgently required. The above-mentioned programs are sensitive to different neutrino-induced reaction mechanisms, challenging nuclear theory not only at low and intermediate energy transfers (up to several hundred MeV) but also requires a good understanding of baryon-resonance excitation and deep inelastic scattering (DIS) mechanisms on nuclei.

The neutrino oscillation program aims at precisely determining oscillation parameters, the neutrino mass ordering and the CP violation phase. Accelerator-based neutrino experiments have neutrino fluxes spanning over a range of energies of a few GeV and use nuclear targets to maximize statistics. As the oscillation probability depends on the neutrino energy, this has to be reconstructed in every neutrino-nucleus scattering event, allowing this way to infer the oscillation pattern from the neutrino interactions with the nuclear target in the far detector. Owing to the DUNE and Hyper-Kamiokande facilities, in the next years, the field will enter the precision era. **The statistical errors, which up to now were limiting the results, will be largely reduced so that the experiments will become much more sensitive to the details of neutrino-nucleus interactions.** The complexity of the problem that needs to be solved therefore arises from the multiple scales involved: from collective nuclear excitations to scattering on partons. Several reaction channels covering a broad range of energy and momentum transfers need to be taken into account because they are all simultaneously probed in a weighted admixture determined by the energy flux profile: low-energy scattering, quasielastic processes, pion production around the $\Delta(1232)$ peak and beyond, up to the opening of a plethora of inelastic channels in the shallow inelastic (SIS) and DIS regions.

In this context, oscillation experiments also perform a rich experimental program devoted to the study of neutrino-nucleus cross sections using their near detectors. This is nowadays the case for T2K, MicroBooNE and NOvA. T2K will imminently complete a significant near detector upgrade. As part of the short-baseline neutrino program at Fermilab, the SBND detector will collect an unprecedentedly large data set of neutrino-argon interactions while ICARUS and MicroBooNE will measure neutrino interactions from two beams of different energies and flavor compositions. The effort will continue with long baseline experiments Hyper-Kamiokande and DUNE. In addition, there are experiments dedicated to investigating neutrino-nucleus scattering such as MINERvA, that keeps delivering relevant measurements after its completion. ENUBET and NuSTORM at CERN and ESSnuSB are

European initiatives that aim to deliver well-understood neutrino beams that would allow precise measurements of cross sections. In particular, a detailed study of electron-neutrino interactions, which is not at reach for other experiments, would be possible at NuSTORM.

Complementary activity to improve on the theoretical modeling of the neutrino-nucleus cross section becomes ever more important. Our understanding of neutrino-nucleus interactions needs to be improved significantly in order to be able to realise the discovery potential of the next generation of experiments. This evolution requires the calculation of relevant electroweak matrix elements and response functions not only at the inclusive level but, particularly, for exclusive channels. Experimental analyses rely on Monte Carlo event generators to bridge the gap between the raw signal in the detector and the extracted cross-sections. This is also the case for assessing systematic errors in neutrino energy reconstruction. Often however, the nuclear models instrumented by these generators are limited in their nuclear physics content, necessitating large systematic uncertainties. To meet these needs, event generators should evolve to provide a flexible interface to advanced models, at the same time ensuring consistency among different ingredients and with external non-neutrino data.

Electroweak nuclear studies relate to other nuclear reactions and directly benefit from the corresponding experiments which can be performed with higher precision. Photon and electron scattering provide information about the vector part of the interaction, while pion-nucleus scattering can be related to the axial current although only in the limit of zero four-momentum transfer squared. Furthermore, as recently shown by the e4ν collaboration, neutrino energy reconstruction techniques can be partially tested with external data. The field will further benefit from experimental data on electron scattering from JLab and MAMI but also from pion and proton scattering on argon from the ProtoDUNE experiments at CERN.

In the following we present in more detail the current status, opportunities and *challenges* of neutrino-nucleus scattering programs at various energy scales. Further details can be found in reviews and white papers [1–9] and in references therein.

II. LOW-ENERGY NEUTRINO-NUCLEUS SCATTERING

At low energies ($E_\nu < 50$ MeV), relevant processes include recently confirmed neutrino-nucleus elastic scattering (CEνNS) and inelastic processes such as the excitation of low-lying nuclear states, nucleon knockout and collective modes. CEνNS has the potential to search for and constrain BSM neutrino interactions and neutrino properties such as electromagnetic radii and magnetic moments, provided that neutron-distribution and weak form factors are accurately constrained by theory with the help of experiment. Parity violating electron scattering and CEνNS are the main source of information about neutron distributions. Therefore, *measurements at different momentum transfers, angular distributions and off different nuclear targets are paramount to disentangle nuclear effects from new physics.*

Accurate calculations of inelastic scattering, including exclusive final states for complex nuclear targets, are also needed to study the dynamics of supernova bursts and the diffuse supernova neutrino background, and to reconstruct the energies of astrophysical neutrinos from such events detected on Earth. This includes the important $\nu_e\,{}^{40}Ar \to e^-\,{}^{40}K^*$ *reaction that will be used at DUNE to investigate supernova and solar neutrinos.*

In this context, *the measurements of inelastic electron-argon cross sections in the tens-of-MeV regime (possible at the future MESA) would greatly facilitate efforts to interpret the data obtained from a possible future observation, as well as the low-energy neutrino-*

nucleus program at SNS. These experiments have a unique sensitivity to electron neutrinos whose measurement is essential as it offers complementary information that is important for astrophysical neutrino studies.

III. NUCLEON-KNOCKOUT PROCESSES

In accelerator-based experiments, several reaction channels covering a broad range of energy and momentum transfers need to be taken into account because they are all simultaneously probed in a weighted admixture determined by the flux energy profile. Experiments try to improve on event-selection by applying restrictions on event topology and by applying kinematic cuts to the data. From an experimental point of view, the quasielastic channel corresponds to reactions that have only one lepton and nucleon in the final state. Although this signal might be contaminated with more involved reaction mechanisms, it is absolutely crucial for oscillation analyses as it provides the most accessible reconstruction of neutrino energies. Despite the fact that this channel has been studied extensively over the past decades, experimental progress and the more general use of Liquid Argon TPC detectors necessitate further improvements towards the description of more exclusive processes, the topologies of final-state particles, and a broader range of target nuclei.

Various models of quasielastic processes are on the market, ranging from performant and flexible mean field models and factorized approaches to ab-initio calculations. Ab-initio methods have proved able to predict nuclear responses not only for light nuclei, but also in the range of medium-mass systems. They consistently treat the dynamics of initial and final-state wave functions and electroweak currents, and provide results with controllable approximations. This is particularly important for the moderate momentum transfer region, which is sensitive to the role of final state interactions and details of nuclear structure. *Extending these approaches towards relativistic kinematics, heavier targets and more exclusive processes however remains a distinct challenge for future research.*

Mean-field or shell-model approaches are able to capture a good part of the nuclear dynamics by describing the ground state nucleus as a set of independent-particle nucleon wave functions that are solutions of the mean-field equations. Nuclear effects like Pauli blocking, binding energy and distortion are consistently incorporated. It is important to stress that mean-field approaches can deal with medium and heavy nuclei in the same way without an excessive additional computational cost. They provide full hadronic information, which is useful to benchmark the calculations of Monte Carlo neutrino event generators.

These models can be complemented with extensions as e.g. spectral functions and RPA corrections, taking into account nuclear correlations beyond those included in the mean-field picture. *For the experimental analyses one has to extend the applicability of nuclear models to higher energies and provide predictions for exclusive channels*, even if this comes at the cost of introducing further approximations.

A significant amount of theoretical and experimental work as well as generator development is devoted to understanding the role played by meson-exchange currents. This mechanism populates the so-called dip region above the quasielastic peak. This interest is justified by the implications this reaction mechanism bears for neutrino energy reconstruction. A variety of nuclear physics approaches have been applied to describe the cross-section with no pions in the final state measured by MiniBooNE and T2K with mean neutrino energies below 1 GeV. The results are overall satisfactory, but the situation changes for experiments that probe higher energy and momentum transfers such as MINERvA and NOvA. *The signature* *of two-nucleon mechanisms in the exclusive final states and their role in calorimetric neutrino energy measurements are still far from being understood.* The implementation in event generators is at present incomplete and inconsistent with the treatment of quasielastic and inelastic processes. The first results from the MicroBooNE for the interactions with exactly two protons in the final state promise more experimental details about these interactions.

IV. THE DELTA(1232) REGION AND BEYOND

Pion production is one of the leading channels in the energy range of interest for experiments with accelerator and atmospheric neutrinos. It can be part of the signal or a background that should be precisely constrained. In spite of the progress, 20-30 % errors are still taken for single-pion production in oscillation analyses due to tensions between data sets and models. To a large extent, single-pion production is driven by $\Delta(1232)$ excitation. The properties of the nucleon-to-Δ axial transition are only partially constrained by data.

An important challenge will be *bridging the transition from the kinematic region described by hadronic degrees of freedom to the one described in terms of quarks and gluons in a reliable way* or, in other words, from non-perturbative to perturbative QCD. The transition region between pion production and DIS is referred to as the shallow inelastic scattering (SIS) region. *Reactions in this SIS regime are only poorly understood both theoretically and experimentally but are bound to contribute significantly to the determination of neutrino oscillation parameters* at NOvA and DUNE but also for atmospheric neutrino measurements at Ice Cube, Super- and Hyper-Kamiokande and KM3NeT.

Based on the information available from electron scattering, neutrino-scattering simulations often describe this transition using parton distribution functions empirically extrapolated from the DIS region to lower values of the invariant mass, W, of the final hadronic system, and four-momentum transferred squared, Q^2. Duality arguments constrain the inclusive cross section but do not predict the specific particle content of the final state. The latter is critical for experiments like DUNE that rely on the measured hadronic energy. Hadronization is usually described by data-driven phenomenological models, but available data are sparse and insufficient to make reliable predictions of the hadronic final states. Therefore, *research to extend the description in terms of quarks and gluons towards lower W and Q^2 by including higher-twist corrections and improved hadronization should be complemented with realistic modeling of the SIS region using hadronic degrees of freedom.* Progress in this direction has been significant but is hindered by the lack of experimental information about the axial current for inelastic processes at non-zero Q^2.

The interpretation of data taken by modern experiments on heavy nuclear targets follows a factorization scheme that combines a description of the initial state, an electroweak single-nucleon matrix element and final-state interactions of the produced hadronic states with the nuclear medium. The role of two-nucleon currents for inelastic processes remains largely unexplored except for a few studies in the $\Delta(1232)$ region. *The unresolved tension between MiniBooNE and MINERvA pion production data that cannot be simultaneously described by theoretical models is not only an open problem for nuclear theorists but also a source of systematic uncertainties for oscillation analyses.*

Several experiments (MicroBooNE, SBND, T2K and DUNE) will measure many rare and suppressed processes. These include Cabibbo-suppressed *single kaon or hyperon production.* Besides, the study of *associated kaon and hyperon production* would reduce the systematic uncertainties of proton decay searches. However, these measurements will *require work* *to incorporate past theoretical results for neutrino scattering and integrate know-how from nuclear physics.* In particular, *work on the treatment of transitions between the nucleon and hyperon nuclear potentials has only recently started.*

V. NUCLEAR MEDIUM EFFECTS IN DIS PROCESSES

The influence of the nuclear medium in the DIS region was first observed by the EMC collaboration using a muon beam, and later confirmed by many more experiments using electromagnetic probes. In the weak sector, several DIS measurements with (anti)neutrino beams using different targets were performed, with the latest by the MINERvA experiment using multiple targets in the same beam. The general observation is that the structure functions that characterize the semi-inclusive cross section on nucleons are different for bound nucleons. Such nuclear medium effects are affected not only by the nuclear mass, but also exhibit dependence on the Bjorken x and the four-momentum transfer square Q^2 variables. There are two broad approaches to understanding the effects of the nuclear medium on structure functions. The phenomenological approach involves determining the effective parton distribution of nucleons within a nucleus, while the theoretical approach considers the dynamics of nucleons in the nuclear medium. In the case of the electromagnetic sector, theoretically, many models have been proposed to study these effects on the basis of nuclear binding and nuclear medium modifications. In spite of these efforts, no comprehensive phenomenological or theoretical understanding of the nuclear modifications across the complete range of x and Q^2 consistent with the presently available experimental data exists. In a recent phenomenological study, it has been concluded that the electromagnetic and weak nuclear structure functions at low x are different. Theoretically, *there have been very few attempts to study nuclear medium effects on the weak structure. To better understand nuclear structure functions in the weak sector, one needs detailed theoretical as well as experimental studies of nuclear medium effects: shadowing, antishadowing, multi-nucleon correlations, on the weak structure functions and compare the results with the electromagnetic structure functions for a wide range of x and Q^2 for moderate as well as heavy nuclear targets.*

VI. CONCLUSIONS

In the coming years, neutrino-nucleus interactions will become ever more important, opening windows to a rich spectrum of new physics. The next generation of experiments will require considerable efforts towards more precise modeling of neutrino-nucleus cross sections. All possible interaction processes on single nucleons or heavier nuclear targets share a limited knowledge of the axial sector that calls for new measurements complemented by improvements in theory and simulations.

Realistic theoretical modeling of scattering should provide accurate predictions of neutrino-nucleus interactions, as well as meaningful theoretical uncertainties. New neutrino cross-section measurements to guide and benchmark model improvements will be essential, as will be sustained support for event generator development and theoretical and computational efforts. **Achieving accurate and precise descriptions of neutrino scattering cross sections over a broad range of energy scales will maximize the potential for discovery as the field moves into the precision era.**

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