NTE CARLO NEUTRINO EVENT GENERATORS

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Monte Carlo neutrino generators are programs or libraries which simulate neutrino interactions with electrons, nucleons and nuclei. In this capacity their usual task is to take an input neutrino and nucleus and produce a set of 4-vectors for particles emerging from the interaction, which are then input to full detector simulations. Since these generators have to simulate not only the initial interaction of neutrinos with target particles, but re-interactions of the generated particles in the nucleus, they contain a wide range of elementary particle and nuclear physics. Viewed more broadly, they are the access point for neutrino experimentalists to the theory inputs needed for analysis. Examples include cross section libraries for event rate calculations and parameter uncertainties and reweighting tools for systematic error evaluation.

Neutrino experiments typically operate in neutrino beams that are neither completely pure nor mono-energetic. Generators are a crucial component in the convolution of beam flux, neutrino interaction physics, and detector response that is necessary to make predictions about observable quantities. Similarly they are used to relate reconstructed quantities back to true quantities. In these various capacities they are used from the detector design stage through the extraction of physics measurements from reconstructed observables. Monte Carlo neutrino generators play unique and important roles in the experimental study of neutrino interactions and oscillations.

There are several neutrino event generators available, such as ANIS [1], GENIE [2], GiBUU [3], NEGN [4], NEUT [5], NUANCE [6], the FLUKA routines NUNDIS/NUNRES [7], and NuWRO [8]. Historically, experiments would develop their own generators. This was often because they were focused on a particular measurement, energy range, or target, and wanted to ensure that the best physics was included for it. These 'home-grown' generators were often tuned primarily or exclusively to the neutrino data most similar to the data that the experiment would be collecting. A major advance in the field was the introduction of conference series devoted to the topic of neutrino interaction physics, NuINT and NuFACT in particular. Event generator comparisons have been a regular staple of the NuINT conference series from its inception, and a great deal of information on this topic can be found in the Proceedings of these meetings. These meetings have facilitated experiment-theory discussions leading to the first generator developed by a theory group (NuWRO) [8], the extension of established nuclear interaction codes (FLUKA and GiBUU) to include neutrino-nuclear processes [3,7], and inclusion of theorists in existing generator development teams.

These activites have led to more careful scrutiny of the crucial nuclear theory inputs to these generators, which is evaluated in particular through comparisons to electron-scattering data. At this point in time all simulation codes face challenges in describing the full extent of the lepton scattering data, and the tension between incorporating the best available theory versus obtaining the best agreement with the data plays out in a variety of ways within the field. For the field to make progress, inclusion of state of the art theory needs to be coupled to global analyses that correctly incorporate correlations between measurements. Given the rapid pace of new data and the complexity of analyses, this is a significant challenge for the field in the coming years.

There are many neutrino experiments which use various sources of neutrinos, from reactors, accelerators, the atmosphere, and astrophysical sources, thereby covering a range of energies from MeV to TeV. Much of the emphasis has been on the few-GeV region in the generators, as this is the relevant energy range for long-baseline neutrino oscillation experiments. These generators use the impulse approximation for most of the primary neutrino interactions and simulate the interactions of secondary particles in the nucleus in semi-classical ways in order to simulate a variety of nuclei in a single model, and for practical considerations as these approaches are fast. However, there are several challenges facing these simulations coming mainly from the complexity of the nuclear physics, and avoiding double counting in combining perturbative and non-perturbative models for the neutrino-nucleon scattering processes. While generators share many common ingredients, differences in implementation, parameter values, and approaches to avoid double counting can yield dramatically different predictions [9]. In the following sections, interaction models and their implementations including the interactions of generated particles in the nuclei are described.

In order to assure its reproducibility, neutrino event generators are tuned and validated against a wide variety of data, including data from photon, charged lepton, neutrino, and hadron probes. The results from these external data tuning exercises are important for experiments as they quantify the uncertainty on model paramaters, needed by experiments in the evaluation of generator-related systematic errors. Electron scattering data plays an important role in determining the vector contribution to the form-factors and structure functions, as well as in evaluating specific aspects of the nuclear model. Hadron scattering data is used in validating the nuclear model, in particular the modeling of final state interactions. Tuning of neutrino-nucleon scattering and hadronization models relies heavily on the previous generation of high energy neutrino scattering and hydrogen and deuterium bubble chamber experiments, and more recent data from the K2K, MiniBooNE, NOMAD, SciBooNE, MINOS, T2K, ArgoNEUT, and MINERvA experiments either has been, or will be, used for this purpose.

42.1. Neutrino-Nucleon Scattering

Event generators typically begin with free-nucleon cross sections which are then embedded into a nuclear physics model. The most important processes are quasi-elastic (elastic for NC) scattering, resonance production, and non-resonant inelastic scattering, which make comparable contributions for few-GeV interactions. The neutrino cross sections in this energy range can be seen in Figures 50.1 through 50.4 of this *Review.*

42.1.1. ***Quasi-Elastic Scattering*** : The cross section for the neutrino nucleon charged current quasi-elastic scattering is described in terms of the leptonic and hadronic weak currents, where dominant contributions to the hadronic current come from the vector and axial-vector form factors. There also exists the pseudo-scalar term (the pseudo-scalar form factor) in the hadronic current but this term is rather small for electron and muon neutrinos and usually related to the axial form factor assuming partially conserved axial current (PCAC). The vector form factors are measured by the recent precise electron scattering experiments and known to have some deviation from the simple dipole form [10]. Therefore, most of the generators use parametrizations of this form factor taken directly from the data. For the axial form factor there is no such precise experiment, and most of the generators use a dipole form. Generally, the value of axial form factor at $q^2 = 0$ is extracted from the polarized nucleon beta decay experiment. However, the selection of the axial vector mass parameter depends on each generator, with values typically around 1.00 GeV/c^2.

42.1.2. ***Resonance Production*** : Most generators use the calculation of Rein-Sehgal to simulate neutrino-induced single pion production [13]. To obtain the cross section for a particular channel, they calculate the amplitude for the production of each resonance multiplied by the probability for the decay of that resonance into that particular channel. Implementation differences include the number of resonances included, whether the amplitudes are added coherently or incoherently, the invariant mass range over which the model is used, how non-resonant backgrounds are included, inclusion of lepton mass terms, and the model parameter values (in particular the axial mass). In this model it is also possible to calculate the cross-sections of single photon, kaon and η productions by changing the decay probability of the resonances, which are included in some of the programs. However, it is known that discrepancies exist between the recent pion electro/photoproduction data and the results from the simulation data with the same framework, i.e. vector part of this model. There are several attempts to overcome this issue [12] and some of the generators started using more appropriate form factors. The GiBUU and NuWRO generators do not use the Rein-Sehgal model, and instead rely directly on electro-production data for the vector contribution and fit bubble chamber data to determine the remaining parameters for the axial contribution [14], [15,16].

42.1.3. ***Deep and Shallow Inelastic Scattering*** : For this process the fundamental target shifts from the nucleon to its quark constituents. Therefore, the generators use the standard expression for the constructions for the nucleon structure functions F_2 and xF_3 from parton distributions for high Q^2 (the DIS regime) to calculate direction and momeuntum of lepton. The first challenge is in extending this picture to the lower values of Q^2 and W that dominate the available phase space for few-GeV interactions (the so-called 'shallow inelastic scattering', or SIS regime). The corrections proposed in [17] are widely used, while others [7] implement their own modifictions to the parton distributions at low Q^2. Both DIS and SIS generates hadrons but their production depends on each generator's implementation of a hadronization model as described in the next section. There are various difficulties not only in the actual hadronization but the relation with the single meson production. It is necessary to avoid double counting between the resonance and SIS/DIS models, and all generators are different in this regard. The scheme chosen can have a significant impact on the results of simulations at a few-GeV neutrino energies.

42.2. Hadronization Models

For hadrons produced via baryonic resonances, the underlying model amplitudes and resonance branching fractions can be used to fully characterize the hadronic system. For non-resonant production, a hadronization model is required. Most generators use PYTHIA [18] for this purpose, although some with modified parameters. In addition some implement their own models to handle invariant masses that are too low for PYTHIA, typically somwhere around 2.0 GeV/c^2. Such models rely heavily on measurements of neutrino hadro-production in high-resolution devices, such as bubble chambers and the CHORUS [19] and NOMAD experiments [20], to construct empirical parametrizations that reproduce the key features of the data [21,22]. The basic ingredients are the emperical observations that average charged particle multiplicites increase logarithmically with the invariant mass of the hadronic system, and that the distribution of charged particle multiplicities about this average are described by a single function (an observation known as KNO scaling). Neutral particles are assumed to be produced with an average multiplicity that is 50% of the charged particle multiplicity. Simple parametrizations to more accurately reproduce differences observed in the forward/backward hemispheres of hadronic systems are included in GENIE, NEUT, and NuWRO.

42.3. Nuclear Physics

The nuclear physics relevant to neutrino-nucleus scattering at few-GeV energies is complicated, involving Fermi motion, nuclear binding, Pauli blocking, in-medium modifications of form factors and hadronization, intranuclear rescattering of hadrons, and many-body scattering mechanisms including long- and short-range nucleon-nucleon correlations.

42.3.1. *Scattering Mechanisms* :

Most of the models used for neutrino-nuclear scattering kinematics were developed in the context of few-GeV inclusive electron scattering, by experiments going back nearly 50 years. A topic of considerable discussion within this community has been to what extent the impulse approximation, whereby the nucleus is envisioned as collection of bound, moving, single nucleons, is appropriate. The question arose initially in the context of measurements of the quasi-elastic axial mass, with a number of recent experiments using nuclear targets measuring values that were significantly higher than those obtained by an earlier generation of bubble chamber experiments using hydrogen or deuterium [23]. These led to a revisitation of the role played by scattering from multi-particle/hole states in the nucleus. The contribution of these scattering processes is an extremely active area of theoretical research at present, with significant implications for generators and analyses [24]. The GiBUU, NuWRO, GENIE, and NEUT generators have all implemented, or are in the process of implementing, first models for these processes [25].

In order to obtain the cross-section off nucleons in the nucleus, it is necessary to take into account the in-medium effects. The basic models imployed in event generators rely on impulse approximation schemes, the most simple of which is the Relativistic Fermi Gas Model. The most common implementations are the Smith-Moniz [26] and

Bodek-Ritchie [27] models. Within the electron scattering community, the analagous calculations have for decades relied on spectral functions, which incorpoate information about nucleon momenta and binding energies in the impulse approximation scheme. The NuWRO and GiBUU generators currently use spectral functions, they are incorporated into NEUT as an option, and several of the other generators are incorporating spectral function models at this time. It is known from photo and electro-nuclear scattering that the Delta width is affected by Pauli blocking and collisional broadening. These effects are included in some, but not all, generators.

When scattering from a nucleus, coherent scattering of various kinds is possible. Most simulations incorporate, at least, neutral and charged coherent coherent single pion production. While the interaction rate for these interactions is typically around a percent of the total yield, the unique kinematic features of these events can make them potential backgrounds for oscillation searches. Implemented in Monte Carlo are PCAC-based methods, while microscopic models are currently being incorporated into several generators as well. Reference [9] clearly demonstrates a point mentioned earlier, where generators implementing the same model [28] are seen to produce very different predictions.

42.3.2. *Hadron Production in Nuclei* :

Neutrino pion production is one of the dominant interactions in a few-GeV region and the interaction cross sections of pions in nucleus from those interactions are quite large. Therefore, the interactions of pions in nucleus changes the kinematics of the pions and can have large effects on the results of simulations at these energies. Most generators implement this physics through an intranculear cascade simulation. In generators which utilize cascade models, a hadron, which has been formed in the nucleus, is moved step by step until it interacts with the other nucleon or escapes from the nucleus. The probabilities of each interaction in nuclus are usually given as the mean free paths and used to determine whether the hadron is interacted or not. If the hadron is found to be interacted, appropriate interactions are selected and simulated. Usually, absorption, elastic, and inelastic scatterings including particle productions are simulated as secondary interactions. The determination method of the kinematics for the final state particles heavily depends on the generators but most of them use experimentally validated models to simulate hadron interactions in nucleus. No two interanuclear cascade simulations implemented in neutrino event generators are the same. In all cases hadrons propagate from an interaction vertex chosen based on the density distribution of the target nucleus. In determining the generated position of the hadrons in nucleus, the concept of the formation length is sometimes employed. Based on this idea, the hadronization process is not instantaneous and it takes some time before generating the hadrons [29]. The basis for formation times are measurements at relatively high energy and Q^2, and most generators that employ the concept do not apply them to resonance interactions, the exception is [29]. The intranuclear rescattering simulations are typically validated against hadron scattering data. In some simulations (e.g. NEUT) the pion-less Delta decay is also considered and 20% of the events do not have a pion and only the lepton and the nucleon are generated.

The exception is GiBUU, a semiclassical transport model in coupled channels that describes the space-time evolution of a manybody system in the presence of potentials and a collision term [3]. This approach assures consistency between nuclear effects in the initial state, such as Fermi motion, Pauli blocking, hadron self-energies, and modified cross sections, and the final state, such as particle reinteractions, since the two are derived from the same model. This model has been previously used to describe a wide variety of nuclear interaction data. Similarly, the hadronic simulation of the NUNDIS/NUNRES programs are handled by the well-established FLUKA hadronic simulation package [7].

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