Brief introduction of the neutrino event generators

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Abstract. The neutrino interaction simulation programs (event generators) play an important role in the neutrino experiments. This article briefly explains what is the neutrino event generator and how it works.

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INTRODUCTION

Since the discovery of the neutrino oscillation by observing the atmospheric neutrino using the Super-Kamiokande (SK) detector[1], several accelerator based long baseline neutino oscillation experiments, like K2K[2], MINOS[3], and T2K[4] started taking data. At the same time, SK continuously accumulates atmospheric neutrino events. Meanwhile, accelerator short baseline neutrino oscillation experiments, MiniBooNE, was started and collected huge amount of events. As a result, large amount of excellent quality neutrino scattering data are now available to study not only the neutrino oscillation phenomena but various neutrino interactions with nucleus.

In order to extract the neutrino oscillation parameters using these data sets, neutrino interaction simulation programs, so-called neutrino event generators, are extensively used. Various distributions from the real data are compared with the simulated data taking into account the oscillation parameters and the systematic uncertainties.

Because the amount of the data for the oscillation analyses are large enough and the dominant error sources of the oscillation parameters are sometimes not statistical but systematic uncertainties. Among of the systematic errors, uncertainties of the neutrino interactions could be one of the major sources of the errors. Therefore, precise understandings of the neutrino interactions are getting very important and simultaniously, the required precision of the event generators are much higher in these days.

In the neutrino experiments, event generators are used to provide information how the signal and the background events are observed in the detectors. Therefore, each generator is expected to simulate all the possible interactions and the simulations of each interaction have to cover entire kinematical region using appropriate models. Of course, it is not possible to simulate all the neutrino interactions perfectly and thus, there are always simplifications and assumptions in the actual implementation of the simulation programs.

Because most of the neutrino detectors, i.e. neutrino interaction target matgerial, are not hydrogen but nucleus. Therefore, it is necessary to simulate the neutrino interaction with nucleus. This means that each event generator is also required to simulate interactions of particles in nucleus, which have been generated from the neutrino interactions.

The outputs from an event generator are 4-momenta of target nucleon(s), outgoing leptons, all the hadrons and gammas exitting from the target nucleus, which are expected to be detected in the detectors. Some of the generators also provide the information on the interactions of hadrons in the target nucleus.

Neutrino event generators are also used to evaluate systematic uncertainties in extracting the physics results. In order to evaluate systematic errors, there are two possible ways. The first one is to simulate again with the other model or the parameter sets in each physics model and evaluate the size of the error. The other way is to calculate the difference of the interaction probability, so-called reweighting method. Of course, there are limitations in the second method but it is efficient and possible to try many patterns. Therefore, some of the neutrino event generators have fucntionalities to perform this kind of 'reweighting' scheme easily.

INCOMPLETE LIST OF EXISTING EVENT GENERATORS

There are several neutrino event generators available in the market. In the early days, each experiment developed their own event generators. NEUT[5], NUANCE[6][7] and NEUGEN[8] are in this category. NEUT was initially developed for the Kamiokande experiment and continuously updated for the Super-Kamiokande, the K2K, the SciBooNE[9] and the T2K experiments. NUANCE was developed for the IMB experiment and used in the other experiments. For example, MiniBooNE [10] has been using NUANCE as the official generator and improved it using the high statistics data of this experiment. NEUGEN was developed for the SOUDAN experiment[11] and has been updated to be used in the MINOS experiment.

Then, there are attempts to develop general purpose generators. FLUKA [12][13] and GENIE [14] are in this category. These event generators are not the simple interaction simulation programs but have additional functionalities like the geometry handling and so on. FLUKA is the general purpose simulation program which simulates interactions of wide variety of particles and it also handles neutrino interactions. GENIE is a generator which is intended to be used in various neutrino experiments. GENIE is designed to be a new universal generator and actually used in several experiments like ArgoNeut[15], MicroBooNE[16], MINOS, MINERνA [17], and T2K. The GENIE collaboration is continuously working to include the latest interaction models.

Recently, there are another kind of event generators, which were developed by theorist groups. GIBUU[18] and NuWro[19] are in this category. GIBUU is aiming to provide an unified transport framework in the MeV to GeV energy regimes for elementary reactions on nuclei, e.g. electron - nucleus, photon - nucleus, hadron - nucleus, heavy ion and neutrino - nucleus collisions. This program library simulates particle transportation in nucleus with numerous nuclear effects with up to date models. NuWro is another event generators developed by Wroclaw group. The main motivation of the authors of NuWro was to have tools to investigate the impact of nuclear effects on directly observable quantities with all the final state interactions included. Now, NuWro simulates all the essential interactions and it is possible to be used in the experiments.

STANDARD FRAMEWORK OF THE GENERATORS

In this section, the standard framework of the neutrino event generator and the physics models used to simulate neutrino interactions are briefly explained.

Most of the neutrino event generators generate an event in two steps. In the first step, a neutrino interaction is simulated and then, the interactions of the generated particles in the nucleus are simulated as the second step.

Primary neutrino interactions in the generators are usually categoraized as follows:

- (Quasi-)elastic scattering ($\nu\ N \rightarrow \ell\ N'$),
- meson productions via resonance ($\nu\ N \rightarrow \ell\ N'\ m$),
- coherent pion production ($\nu X \rightarrow\ \ell\ \pi\ X$),
- Deep inelastic scattering ($\nu N\ \rightarrow \ell\ N'\ hadrons$),

where N, ℓ, m, X denote nucleon, lepton, meson and nucleus, respectively. In the recent neutrino event generators, several other interactions are also simulated to explain the results from the recent high statistics experiments.

The formalism of quasi-elastic scattering off a free proton used in the simulation programs, is described by Llewellyn-Smith [20]. In this formulation, there are two form factors, vector and axial vector form factors. Originally, dipole shape has been used for both form factors. However, it turned out that dipole shape is not perfect for the vector form factor. Therefore, most of the generators use more complicated form, which has been extracted from the recent results of various electron scattering experiments. The axial vector form factor needs to be extracted from the neutrino interactions and thus, still dipole shape is assumed. In order to simulate CCQE in the nucleus, some of the simulators use relativistic Fermi-gas models, like the one by Smith and Moniz [21]. The other recent simulators use more sophisticated models and take into account the realistic momentum and potential distributions of nucleon in the nucleus (spectral functions), short range correlations, local density models of nucleus, the random phase approximation and so on.

The resonance productions are simulated using the model by Rein and Sehgal[22] in the traditional event generators. Because it is possible to take into account all the resonances below $2GeV/c^2$ and the interferences of the resonances are also considered in calculating the cross-sections and kinematics of the particles using this model. However, the simulated results of electron scatterings and photo-productions with the event generator, which uses same framework as the one in Rein-Sehgal's model, show differences if we compare with the recent experimental results. There are attempts to modify the structure functions to give better agreements to overcome this problem.[23] Recently, more sophisticated models are developed to simulate resonace productions and used in some generators, like GIBUU and NuWro.

There is another type of pion production, so-called coherent pion production. In this interaction, a neutrino is scattered with the nucleus and pion is created but the nucleus stays the same. This interaction is known to exist in the high energy region, i.e. above several GeV, and modeled by Rein and Sehgal[24] This model predicts not only the neutral current but the charged current. The cross-section of neutral current coherent pion productions seemed to agree with the recent measurements. On the other hand, the measured charged current cross-sections in K2K and SciBooNE were very small below 1.5 GeV or so compared to the predictions.[25]Since then, several modifications to the Rein and Sehgal's model and new models have been proposed and each event generator uses the models, which they think is most appropriate for their purpose.

In simulating the deep inelastic scattering, standard structure functions, F2 and xF3, are used. Here, most of the generator apply corrections for the low q^2, small intermediate hadron invariant mass (W) interactions, based on the formulation by Bodek and Yang[27]. Because the usual form factors (parton distribution functions) are not applicable in this kinematical region. Therefore, Bodek and Yang fit the existing data to extract the correction factors on the the structure functions F2 and made reasonable assumption on xF3.

In the last decade, K2K and MiniBooNE reported the deficits of the foward going muons and also enhancement in the rate of the CCQE like events around and below 1 GeV. These discrepancies have been reproduced by changing the axial vector mass larger by $\sim$ 20% or more. However, the value of the axial vector mass is expected to be $\sim 1GeV/c^2$. Because these two experiments uses Carbon and Oxygen as the neutrino interaction target, these discrepancies could be coming from the difference of interactions between nucleon and nucleus. Recently, several models try to explain these differences by taking account the multi-nucleon correlation in the nucleus target. Some of the event generators, like GENIE, GIBUU and NuWro, already incorporate these interactions and the working group of NEUT is also trying to implement this kind of effects. Unfortunately, existing neutrino scattering data are not sufficient to confirm whether these differences are really coming from the multi-nucleon effects or not. However, the experiments like MINERνA, MicroBooNE and T2K are expected to provide further information on this issue in near future.

The interactions of hardons are also taken care of as described in the beginning. Basically, there are two ways in simulating these interactions. (GIBUU uses more sophisticated model. See the reference of transport model of GIBUU[18]) The first one is to use the cascade model and trace the produced hadrons in the nuclear medium until they escape from the nucleus. The other is more simplified model and produce the final state particles from the nucleus using the type of the particle and its location and momentum. The actual implementations of interactions of hadrons in nucleus, like the model of the nucleus, the interaction probabilities, the determination procedures of the kinematics of the scattering particles and so on, are quite different in each event generator. For further detail, please refer to the references of each simulation program.

As described, actual implementations of the models are different in the generators. Therefore, the results may be different between the generators even if they use the same model. This is why it is also important to compare various kinematical distributions from different generators.

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