THE GENIE NEUTRINO MONTE CARLO GENERATOR*

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(Received July 2, 2009)

The exploration of the neutrino mixing matrix forms one of the major directions in science. A number of scientific opportunities lie ahead: Over the next decade searches for $\nu_\mu \rightarrow \nu_e$ oscillations will dramatically improve our sensitivity to θ_{13}, potentially opening a window to exploring CP violation in the lepton sector. Precision measurements of θ_{23} from high statistics ν_μ disappearance studies will shed more light on the neutrino mixing matrix and, possibly, elucidate its relation with the quark mixing matrix. Over a similar time-scale, exploiting matter effects, we will probe the neutrino mass hierarchy. Much of the research program will be carried out with accelerator-made neutrino beams in the few-GeV energy range, the challenging boundary between the non-perturbative and perturbative regimes where our lacking physics descriptions are now being exposed by increasingly precise neutrino data. Advancing our understanding of fundamental neutrino properties, will require building a more complete picture of neutrino interactions and reducing the corresponding systematics to the $\sim 1\%$ level. This will pose a series of important theoretical and experimental challenges. Neutrino generators, the interface between theory and experiment, are in the core of this effort. The 45th Winter School in Theoretical Physics at Lądek-Zdrój was a unique event in the effort to improve neutrino interaction descriptions. Secluded in the Polish countryside, inquiring students, the authors of mainstream neutrino generators representing many experimental communities, and leading theorists had the opportunity to delve into modeling issues, question physics assumptions and probe the accuracy of neutrino simulations. This was a very instructive experience for everyone involved. The goal of this brief note is to refresh the students on some of the physics and technical points discussed during the GENIE lectures.

PACS numbers: 07.05.Tp, 13.15.+g

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* Presented at the 45th Winter School in Theoretical Physics "Neutrino Interactions: From Theory to Monte Carlo Simulations", Lądek-Zdrój, Poland, February 2–11, 2009.

1. Introduction

Neutrino generators are the interface between theory and experiment. As such, they play a variety of important roles in neutrino experiments, from conception to the final physics publication. They are used to evaluate the feasibility and physics reach of proposed experiments, optimize the detector design, analyze the collected data samples and evaluate systematic errors. This multitude of roles makes neutrino generators impressively polymorphic tools and the students of the Karpacz Winter School quickly realized that they were putting an important skill under their belt. In different contexts neutrino generators can be seen, amongst other things, as:

- Front-ends for fast neutrino event generation and 4-vector level studies.
- Back-ends in the full simulation chains of neutrino experiments, integrating complex beam-line simulations and detailed detector geometry descriptions derived from CAD engineering drawings.
- Neutrino cross-section libraries.
- Event re-weighting engines allowing propagating neutrino interaction uncertainties into any observable distribution for the purpose of quantifying systematics.
- Data-bases for a host of experimental data, used in validating and tuning neutrino interaction models and hadronic simulations.
- Fully fledged electron–nucleus and hadron–nucleus event generators for comparing aspects of neutrino interaction simulations, and in particular the nuclear model and intranuclear hadron transport model, with much more abundant data from non-neutrino probes.

GENIE provides a modern and versatile platform for a universal, 'canonical' Neutrino Interaction Physics Monte Carlo whose validity will extend to all nuclear targets and neutrino flavors over a wide range of energies from MeV to PeV scales. Currently the physics model development and validation effort has focused primarily on the challenging few-GeV range, which is relevant for the current and near future long-baseline precision neutrino experiments using accelerator-made beams. The project is supported by a group of physicists from all major experiments operating in this energy range, establishing GENIE as a major HEP event generator collaboration. GENIE has already been adopted by many neutrino experiments, including those using the JPARC and NuMI neutrino beamlines, and will be an important physics tool for the worldwide accelerator neutrino program.

This note provides a brief description of the neutrino interaction physics model in GENIE, and serves to remind the students of the GENIE technical capabilities and tools used during the school exercises. A lot more GENIE information is posted in these proceedings: See Dobson's contribution on neutrino event reweighting [1], Dytman's contribution on intranuclear hadron transport modeling [2], and Gallagher's contribution on generator validation and systematic error evaluation [3].

2. Neutrino interaction physics models in GENIE

The set of physics models used in GENIE incorporates the dominant scattering mechanisms from several MeV to several hundred GeV and are appropriate for any neutrino flavor and target type. Over this energy range, many different physical processes are important.

2.1. Neutrino cross-section model

Neutrinos can scatter off a variety of different 'targets' including the nucleus (via coherent scattering), individual nucleons, quarks within the nucleons, and atomic electrons. The modeling of the most important neutrino scattering processes in the few-GeV energy range is outlined below.

Quasi-elastic scattering (*e.g.* $\nu_\mu + n \rightarrow \mu^- + p$) is modeled using an implementation of the Llewellyn-Smith model [4]. In this model the hadronic weak current is expressed in terms of the most general Lorentz-invariant form factors. Two are set to zero as they violate G-parity. Two vector form factors can be related via CVC to electromagnetic form factors which are measured over a broad range of kinematics in electron elastic scattering experiments. Several different parametrizations of these electromagnetic form factors including Sachs [5], BBA2003 [6] and BBBA2005 [7] models are available with BBBA2005 being the default. Two form factors — the pseudo-scalar and axial vector, remain. The pseudo-scalar form factor is assumed to have the form suggested by PCAC, which leaves the axial form factor $F_{\mathrm{A}}(Q^2)$ as the sole remaining unknown quantity. $F_{\mathrm{A}}(0)$ is well known from measurements of neutron beta decay and the Q^2 dependence of this form factor can only be determined in neutrino experiments and has been the focus of a large amount of experimental work over several decades. In GENIE a dipole form is assumed, with the axial vector mass $\mathrm{m_A}$ remaining as the sole free parameter with a default value of 0.99 GeV/c^2. For nuclear targets a suppression factor is included from an analytic calculation of the rejection factor in the Fermi Gas model, based on the simple requirement that the momentum of the outgoing nucleon exceed the Fermi momentum k_{F} for the nucleus in question. Typical values of k_{F} are 0.221 GeV/c for nucleons in ^{12}C, 0.251 GeV/c for protons in ^{56}Fe, and 0.256 GeV/c for neutrons in ^{56}Fe.

Elastic neutral current processes are computed according to the model described by Ahrens *et al.* [8], including the strange quark contribution to the axial form factor. For nuclear targets the same reduction factor described above is used.

The production of baryon resonances in neutral and charged current channels is included using an implementation of the Rein–Sehgal model [9]. This model employs the Feynmann–Kislinger–Ravndal [10] model of baryon resonances, which give wavefunctions for the resonances as excited states of a 3-quark system in a relativistic harmonic oscillator potential with spin-flavor symmetry. In the Rein–Sehgal paper the helicity amplitudes for the FKR model are computed and used to construct the cross-sections for neutrino-production of the baryon resonances. From the 18 resonances of the original paper we include the 16 that are listed as unambiguous at the latest PDG baryon tables and all resonance parameters have been updated. For tau neutrino charged current interactions an overall correction factor to the total cross-section is applied to account for neglected form factors in the original model. In our implementation of the Rein–Sehgal model interference between neighboring resonances has been ignored.

Deep (and not-so-deep) inelastic scattering (DIS) is calculated in an effective leading order model using the modifications suggested by Bodek and Yang [11] to describe scattering at low Q^2. In this model higher twist and target mass corrections are accounted for through the use of a new scaling variable and modifications to the low Q^2 parton distributions. The cross-sections are computed at a fully partonic level (the $\nu q \to l q'$ cross-sections are computed for all relevant sea and valence quarks). The longitudinal structure function is taken into account using the Whitlow R[1] parameterization [12]. An overall scale factor of 1.032 is applied to the predictions of the Bodek–Yang model to achieve agreement with the measured value of the cross-section at high energy. For nuclear targets a nuclear modification factor is included to account for observed differences between nuclear and free nucleon structure functions which include shadowing, anti-shadowing, and the EMC effect [11].

Coherent scattering results in the production of forward going pions in both charged current ($\nu_\mu + A \to \mu^- + \pi^+ + A$) and neutral current ($\nu_\mu + A \to \nu_\mu + \pi^0 + A$) channels. Coherent neutrino–nucleus interactions are modeled according to the Rein–Sehgal model [13]. Since the coherence condition requires a small momentum transfer to the target nucleus, it is a low-Q^2 process which is related via PCAC to the pion field. The Rein–Sehgal model begins from the PCAC form at $Q^2 = 0$, assumes a dipole dependence for non-zero Q^2 and then calculates the pion–nucleus scattering cross-section

[1] $R = F_{\mathrm{L}}/2xF_1$.

using various nuclear physics assumptions. The GENIE implementation is using the modified PCAC formula described in a recent revision of the Rein–Sehgal model [14] that includes lepton mass terms.

GENIE also simulates many other, more rare, processes including quasi-elastic and deep-inelastic charm production, νe-elastic scattering and inverse muon decay. Full details are given in [15].

The GENIE default cross-section for charged-current inclusive scattering from an isoscalar target, together with the estimated uncertainty, is shown in Fig. 1.

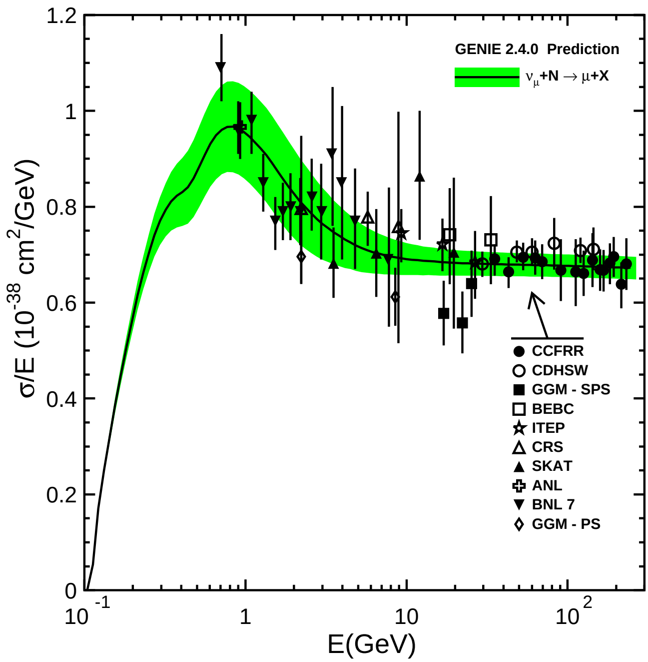


Fig. 1. GENIE default cross-sections for charged current scattering from an isoscalar target. The shaded band indicates the estimated uncertainty on the free nucleon cross-section.

2.2. *Neutrino-induced hadronic multiparticle production modeling*

Neutrino-induced hadronic shower modeling is an important aspect of the intermediate energy neutrino experiment simulations, as non-resonant inelastic scattering becomes the dominant interaction channel for neutrino energies as low as 1.5 GeV. Experiments are sensitive to the details of hadronic system modeling in many different ways. Physics analysis, for example, can depend on the prediction of the hadron shower characteristics, such as shower shapes, energy profile and particle content, primarily for event identification.

A characteristic example is a $\nu_\mu \to \nu_e$ appearance analysis, where the evaluation of backgrounds coming from NC events, would be quite sensitive to the details of the NC shower simulation and specifically the π^0 shower content.

GENIE uses the AGKY hadronization model [16]. This model, which has been tuned primarily to bubble chamber data on hydrogen and deuterium targets, integrates an empirical low-invariant mass model with PYTHIA/JETSET at higher invariant masses. The transition between these two models takes place over an adjustable window with a default range of 2.3 GeV/c^2 to 3.0 GeV/c^2, so as to ensure continuity of all simulated observables as a function of the invariant mass. For the hadronization of low-mass states the model proceeds in two phases, first determining the particle content of the hadronic shower, and secondly determining the 4-momenta of the produced particles in the hadronic center of mass.

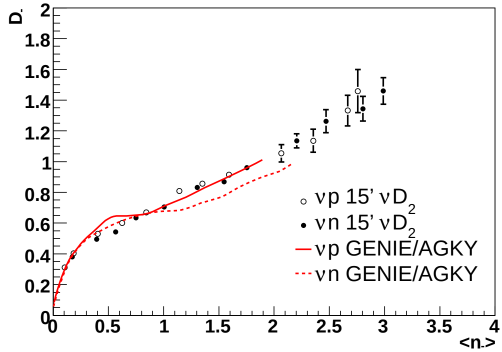
The AGKY's low mass hadronization model generates hadronic systems that typically consist of exactly one baryon (p or n) and any number of π^+, π^-, π^0, K^+, K^-, K^0, $\bar{K^0}$ mesons kinematically possible and allowed by charge conservation.

The first step for simulating the hadron shower particles is the calculation of the average charged hadron multiplicity. The AGKY model uses empirical expressions of the form $\langle n_{\rm ch}\rangle = a_{\rm ch} + b_{\rm ch} * \ln W^2$. The coefficients $a_{\rm ch}$, $b_{\rm ch}$, which depend on the initial state (neutrino and struck nucleon), have been determined by bubble chamber experiments and are treated as tuning parameters. Once the average charged hadron multiplicity has been determined, the average hadron multiplicity is computed as $\langle n_{\rm tot}\rangle = 1.5\langle n_{\rm ch}\rangle$. The actual hadron multiplicity is generated taking into account that the multiplicity dispersion is described by the KNO scaling law, ($\langle n\rangle P(n) = f(n/\langle n\rangle)$) [17], where f is the scaling function. The KNO scaling is parametrized employing the Levy[2] function with an input parameter $c_{\rm ch}$ that depends on the initial state and is treated as a tuning parameter. Once the actual hadron multiplicity has been generated, hadrons up this multiplicity are created taking into account the hadron shower charge conservation and the kinematical constraints. Protons and neutrons are produced in the ratio 2:1 for νp interactions, 1:1 for νn and $\bar{\nu} p$, and 1:2 for $\bar{\nu} n$ interactions. Charged mesons are then created in order to balance charge, and the remaining mesons are generated in neutral pairs. The probabilities for each are 31.33% (π^0, π^0), 62.66% (π^+, π^-), 1.5% (K^0, K^-), 1.5% (K^+, K^-), 1.5% $(\bar{K^0}, K^+)$ and 1.5% $(K^0, \bar{K^0})$. The probability of producing a strange baryon via associated production is determined from a fit to Λ production data:

$$P_{\rm hyperon} = a_{\rm hyperon} + b_{\rm hyperon}\ \ln W^2\,. \tag{1}$$

[2] The Levy function $Levy(z;c) = 2e^{-c}c^{cz+1}/\Gamma(cz+1)$.

Figure 2 shows the data/model comparisons of the negatively charged hadron multiplicity dispersion D_- as a function of the average charged hadron multiplicity $\langle n_- \rangle$ and of the reduced dispersion $D_-/\langle n_- \rangle$ as a function of the squared hadronic invariant mass.



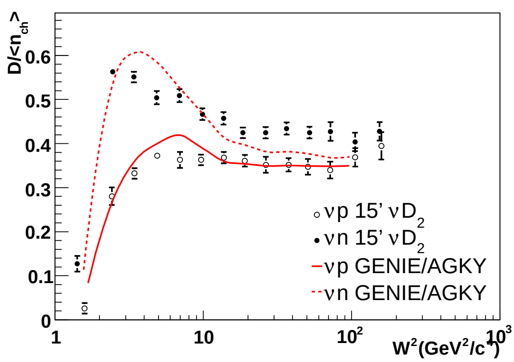


Fig. 2. Data/model comparisons of the negatively charged hadron multiplicity dispersion D_- as a function of the average charged hadron multiplicity $\langle n_- \rangle$ (top) and the reduced dispersion $D_-/\langle n_- \rangle$ as a function of the squared hadronic invariant mass (bottom).

The main dynamical feature observed in the study of hadronic systems is that the baryon tends to go backwards in the hadronic center of mass and that the produced hadrons have small transverse momentum relative to the direction of momentum transfer. At low invariant masses energy-momentum constraints on the available phase space play a particularly important role. The most pronounced kinematical feature in this region is that one of the produced particles (proton or neutron) is much heavier that the rest (pion and kaons) and exhibits a strong directional anticorrelation with the momentum transfer. Our strategy is to correctly reproduce the final state nucleon momentum, using input p_T^2 and x_F PDFs which are parametrized based on experimental data [18,19], and then perform a phase space decay on the remnant system. The phase space decay employs a rejection method suggested in [20], with a rejection factor $e^{-A*p_{\rm T}}$ for each meson. This causes the transverse momentum distribution of the generated mesons to fall exponentially with increasing $p_{\rm T}^2$. Here $p_{\rm T}$ is the momentum component perpendicular to the current direction. More details can be found in [15] and [16].

Figure 3 shows the data/model comparisons of the fragmentation function for positively and negatively charged hadrons. 2-body hadronic systems are a special case: The hadronic system 4-momenta are generated by a simple unweighted phase space.

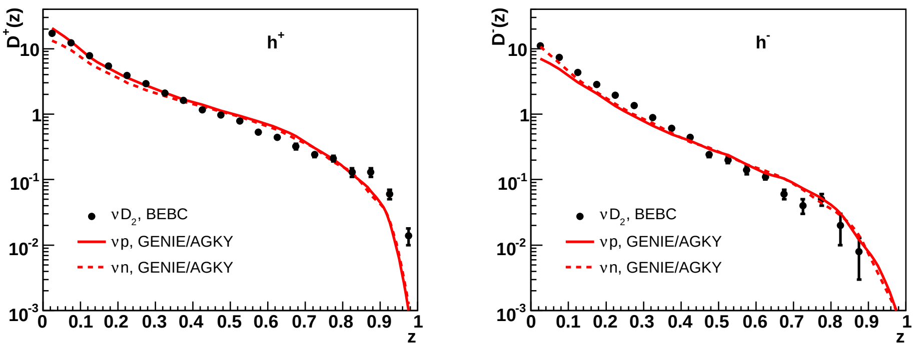


Fig. 3. Data/model comparisons of the fragmentation function for positively and negatively charged hadrons.

2.3. Intranuclear hadron transport modeling

Hadrons produced in the nuclear environment may rescatter on their way out of the nucleus, and these reinteractions significantly modify the observable distributions in most detectors. The effect is two-fold: Reinteractions can change the observed event topology and degrade the hadron energies. These effects are illustrated in Table I and Fig. 4, respectively. The sensitivity of a particular experiment to intranuclear rescattering depends strongly on the detector technology, the energy range of the neutrinos, and the physics measurement being made.

It is also well established that hadrons produced in the nuclear environment do not immediately reinteract with their full cross-section. The basic picture is that during the time it takes for quarks to materialize as hadrons, they propagate through the nucleus with a dramatically reduced interaction probability. This was implemented in GENIE as a simple 'free step' at the start of the intranuclear cascade during which no interactions can occur. The formation time is the only free parameter and is 0.523 fm/c according to the SKAT model [21].

TABLE I

Occupancy of primary and final state hadronic systems for interactions off O^{16} computed with GENIE v2.4.0. The off-diagonal elements illustrate and quantify the topology changing effect of intranuclear rescattering.

Final-state	Primary hadronic system $0\pi X$	$1\pi^0 X$	$1\pi^+ X$	$1\pi^- X$	$2\pi^0 X$	$2\pi^+ X$	$2\pi^- X$	$\pi^0\pi^+ X$	$\pi^0\pi^- X$	$\pi^+\pi^- X$
$0\pi X$	**293446**	12710	22033	3038	113	51	5	350	57	193
$1\pi^0 X$	1744	**44643**	3836	491	1002	25	1	1622	307	59
$1\pi^+ X$	2590	1065	**82459**	23	14	660	0	1746	5	997
$1\pi^- X$	298	1127	1	**12090**	16	0	46	34	318	1001
$2\pi^0 X$	0	0	0	0	**2761**	2	0	260	40	7
$2\pi^+ X$	57	5	411	0	1	**1999**	0	136	0	12
$2\pi^- X$	0	0	0	1	0	0	**134**	0	31	0
$\pi^0\pi^+ X$	412	869	1128	232	109	106	0	**9837**	15	183
$\pi^0\pi^- X$	0	0	1	0	73	0	8	5	**1808**	154
$\pi^+\pi^- X$	799	7	10	65	0	0	0	139	20	**5643**

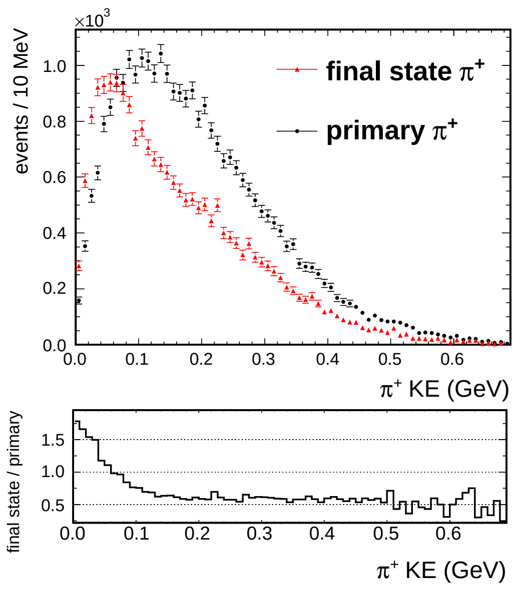


Fig. 4. Kinetic energy spectrum of final state and primary (before rescattering) π^+ produced in $\nu_\mu Fe^{56}$ interactions at 1 GeV.

Intranuclear hadron transport in GENIE is handled by a subpackage called INTRANUKE, an intranuclear cascade simulation, which has gone through numerous revisions since the original version was developed for use by the Soudan 2 Collaboration [22]. Two approaches to simulating intranuclear hadron transport are being pursued within INTRANUKE, named as the 'hA' and 'hN' models. In the following we will focus on the 'hA' model that was chosen as the default model in GENIE v2.4.0.

The complexity of intranuclear hadron transport makes it difficult to evaluate the probability for a generated multi-particle final state, given a primary hadronic multi-particle system, without resorting to a Monte Carlo method. Subsequently, is not possible to evaluate how that probability ought to be modified in response to changes in the fundamental physics inputs. As a result it is generally not possible to build comprehensive reweighing schemes for intranuclear hadron-transport simulations. In this regard GENIE's INTRANUKE/hA model is unique by virtue of the simplicity of the simulation while, at the same time, it exhibiting very reliable aspects by being anchored to key hadron–nucleon and hadron–nucleus data. Its simplicity allows a rather straightforward probability estimate for the generated final state making it amenable to reweighing. A full systematic analysis of the model is therefore possible making it a unique tool in the analysis of neutrino data (see Dobson's contribution to these proceedings [1]).

The simulation tracks pions and nucleons through the nucleus in steps of 0.05 fm. For each hadron being propagated within the nuclear environment its rescattering probability, $P^h_{\rm rescat}$, is calculated as

$$P^h_{\rm rescat} = 1 - \int e^{-r/\lambda^h(\vec{r},h,E_h)} dr \,, \tag{2}$$

where λ^h is the mean free path and the integral is evaluated along the hadron trajectory. The mean free path is a function of the hadron type, h, the hadron energy, E_h, and its position, $\vec{r}$, within the target nucleus and is computed as

$$\lambda^h = 1/(\rho_{\rm nucl}(r) * \sigma^{hN}(E_h)) \,, \tag{3}$$

where $\sigma^{hN}(E_h)$ is the corresponding measured hadron–nucleon cross-section[3] [23] and $\rho_{\rm nucl}(r)$ is the measured charge density [24]. All nuclei heavier than oxygen are modeled with a Woods–Saxon density distribution and lighter nuclei are modeled with a modified Gaussian distribution:

$$\rho_{\rm nucl}(r) = \rho_0 \left[1 + \alpha \left(\frac{r}{a} \right)^2 \right] e^{-r^2/a^2} \,. \tag{4}$$

One difficulty in this approach is that our treatment is using a semiclassical model to describe a quantum mechanical process. This poses particular

[3] We use the isospin-averaged total cross-sections for pions and nucleons and isospin relations for π^0–nucleon reactions.

difficulty in describing elastic scattering which dominates the total cross-section at low energy. This wave/particle distinction depends on energy, with lower energy hadron–nucleus scattering being more wave-like. To account for this we increase the size of the nuclear density distribution through which the particle is tracked by an amount

$$f\frac{hc}{p}\,, \tag{5}$$

where f is an adjustable dimensionless parameter set to 0.5 in the current default.

Hadron–nucleus interactions occur with different processes and each has an associated cross-section — σ_{elas} for elastic scattering, σ_{inel} for inelastic scattering (which includes single nucleon emission), σ_{cex} for single charge exchange for all hadrons. For pions, emission of 2 or more nucleons with no pion in the final state is called absorption — σ_{abs}; for nucleons, a final state with 2 or more nucleons is called multi-nucleon knockout — σ_{ko}. The total cross-section (σ_{tot}) is the sum of all component cross-sections and the total reaction cross-section (σ_{reac}) is the sum of all inelastic reactions,

$$\sigma_{\mathrm{reac}} = \sigma_{\mathrm{cex}} + \sigma_{\mathrm{inel}} + \sigma_{\mathrm{abs}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{elas}}\,. \tag{6}$$

Once it has been determined that a hadron reinteracts in the nucleus, the type of the interaction is determined based on the measured cross-sections for the above listed processes. In some cases, where data is sparse, cross-section estimates are taken from estimates by the CEM03 group [25]. The rescattering mode fractions, as a function of the hadron kinetic energy, are shown in Figs 5 and 6.

Once the interaction type has been determined, the four-vectors of final state particles need to be generated. Where possible these distributions are parametrized from data or from the output of more sophisticated nuclear models [26]. Very low energy hadrons and nuclear recoils are not seen, so simplifications can be made. All states where more than 5 nucleons are emitted are treated as though 5 nucleons (3 protons and 2 neutrons) were emitted. The energy and momentum of the rescattered proton are distributed among the final state nucleons according to phase space.

The intranuclear rescattering model has been tested and tuned based on comparisons to hadron–nucleus data. Fig. 7 shows the comparison between INTRANUKE and data for π^+–Fe total and reaction cross-sections. Validation of the model against neutrino data on nuclear targets have also been performed [22]. Although the model is tuned to hadron scattering on iron, the simplicity of the Fermi Gas model and the $\mathrm{A}^{(2/3)}$ scaling of the cross-sections allow the model to be applied to nearly all nuclei encountered in the simulation as well.

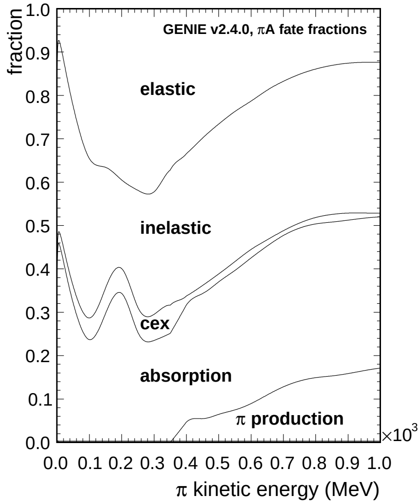


Fig. 5. The default fate fractions for rescattered pions in INTRANUKE/hA (GENIE v2.4.0). The area that corresponds to each pion fate represents the probability for that fate as a function of the pion kinetic energy. The probabilities shown here conditional upon the pion interacting so they always add up to 1.

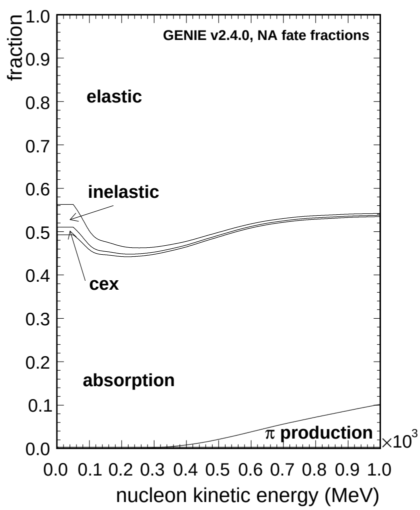


Fig. 6. The default fate fractions for rescattered nucleons in INTRANUKE/hA (GENIE v2.4.0). The area that corresponds to each nucleon fate represents the probability for that fate as a function of the nucleon kinetic energy. The probabilities shown here conditional upon the nucleon interacting so they always add up to 1.

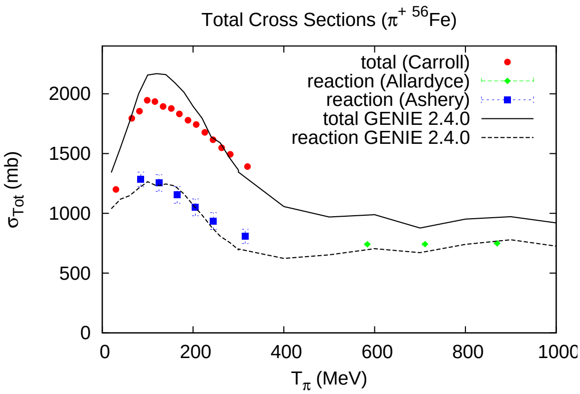


Fig. 7. Pion scattering cross-sections from iron.

3. Using GENIE

GENIE is distributed along with many generic or experiment-specific event generation applications. At the time of writing this article, GENIE included a host of flux drivers allowing it to be used in many realistic, experiment-specific situations. More specifically, it includes an interface to the JPARC neutrino beam simulation [27] used by Super-Kamiokande, nd280, and INGRID and an interface to the NuMI beam simulation [28] used by MINOS, NOvA, MINERvA, MicroBooNE and ArgoNEUT. It also includes drivers for the BGLRS [29] and the FLUKA [30] atmospheric fluxes. GENIE has geometry navigation capabilities, allowing it to generate events using detailed Geant4 or ROOT-based detector geometry descriptions. There is a suite of additional utilities bundled-in GENIE allowing users, amongst other things, to prepare inputs for event generation jobs, analyze event samples and convert the native GENIE event formats to formats expected by experiment-specific detector-level simulations.

GENIE, as a class library, enables users to use off-the-shelf components and build-up their own, specialized event generation or other applications. However, as the suite of standard GENIE applications is fairly complete, most users will only ever interact with these. During the school exercises and tutorials we used, primarily, four GENIE applications. The purpose of each application is outlined below.

- *gmkspl*: Calculates neutrino cross-section splines, using the currently enabled set of physics models and chosen values of physics parameters. The splines are then stored in an XML file which can be fed in the event generation applications speeding them up significantly.

- *gevgen*: Is a generic event generation application. It allows users to describe simple neutrino fluxes of, potentially, multiple neutrino species, each with an energy spectrum specified via ROOT histograms, vector files or analytical parametrizations. Neutrinos are scattered off a simple target mix (a list of targets, each with its own weight fraction) using the full array of currently enabled processes.
- *gT2Kevgen*: Is a T2K-specific event generation application. It uses the detailed JPARC neutrino flux description, by reading-in the JNUBEAM beam-line simulation output ntuples, and handles the realistic geometry description of the T2K detectors (similar application exists for the NuMI beam-line experiments).
- *gntpc*: This is the standard GENIE ntuple conversion utility. During the school we used this tool extensively to analyze the generated event samples and write out simpler summary ntuples.

Detailed instructions and examples on the how to run the GENIE utilities can be found at the GENIE Physics and User manual [31].

4. Summary

GENIE provides a modern and versatile platform for a universal, 'canonical' Neutrino Interaction Physics Monte Carlo whose validity will extend to all nuclear targets and neutrino flavors over a wide range of energies from MeV to PeV scales. Currently, it includes state-of-the-art neutrino interaction physics modeling in the few-GeV energy range which is relevant for the current and near future long-baseline precision neutrino experiments using accelerator-made beams.

I would like to thank the organizers of the 45th Karpacz Winter School in Theoretical Physics, for their invitation to lecture on GENIE. I would like to thank, in particular, Jan Sobczyk, Artur Ankowski and Cezary Juszczak for their kind hospitality and tireless support during the school.

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