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ELEMENTARY PARTICLE PHYSICS

PRELIMINARY RESULTS OF NEUTRINO INTERACTIONS STUDY USING GENIE EVENT GENERATOR*

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Abstract. With the advent of intense accelerator-based sources of neutrinos and the demand of neutrino oscillation experiments to more precisely determine signal and background rates in their detectors has precipitated a resurged interest for neutrino interactions in the few-GeV energy range. Such measurements have not been updated for decades, having first been measured in bubble and spark chamber experiments. New measurements are sorely needed and yield important constraints for present and future neutrino oscillation experiments operating in this energy range. In the present contribution, we studied neutrino interactions in the few-GeV energy range. We used GENIE, a new neutrino Monte Carlo generator, to generate events and compute the cross sections for neutrino-nucleus interactions. Events are generated for particular user-defined situation: neutrinos scattered off a fix nuclear target (^{40}Ar nucleus). We present the obtained results, after we analyzed the event samples, on relevant distributions for the primary lepton created in the events.

Key words: neutrino physics, neutrino event generator, cross-section, GENIE.

1. INTRODUCTION

Neutrinos are very special particles, have only weak interactions, except gravity, and are produced in very different processes in Nuclear and Particle Physics. Also, neutrinos can give us information on processes happening in the Universe, during its evolution, which cannot be studied otherwise. The first major successful detection of neutrinos from space is from the supernova SN-1987A and from solar processes. The Raymond Davies pioneered experiment and the results of the Kamiokande underground experiment (Japan), opened the field of low energy

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neutrino astrophysics, confirmed by the Nobel Prize in 2002. These underground instruments, thanks to technical breakthroughs, have achieved new fundamental results like the solution of the solar neutrino puzzle and the evidence for physics beyond the Standard Model of elementary interactions (SM) in the neutrino sector with non-vanishing neutrino masses and lepton flavour violation.

Understanding Charged-Current (CC) neutrino–nucleus interactions in the few-GeV energy region is very important for many current and future neutrino experiments. The study of neutrino–nucleus reactions in this region is complicated and requires many intermediate steps, such as a description of the nuclear model, understanding the neutrino–nucleon cross sections, modeling of hadronization, as well as the modeling of intranuclear hadron transport and other secondary interactions. These can all play a significant role in how we understand the nature of neutrinos as well as providing useful information about nuclear phenomena. Because of this, there are a number of Monte Carlo generators and numerical packages dedicated to the description of neutrino interactions: GENIE [1], GiBUU [2], FLUKA [3], NEUT [4], NuWro [5] and Nuance [6] represent a large fraction of such generators.

GENIE is a ROOT [7]-based Neutrino Monte Carlo (MC) Generator. Costas Andreopoulos, for the purpose of the MINOS Collaboration, designed it using object-oriented methodologies and developed entirely in C++. Its installation on a LINUX distribution required more external packages to enable certain specialized features: ROOT, LHAPDF [8], PYTHIA6 [9] and other C++ libraries. After almost 4 years of development, the GENIE Collaboration has created a nearly universal neutrino physics MC generator, an important tool for physics exploitation for the next decade. By being universal, GENIE hopes to combine all the knowledge present in existing MC generators within a single framework, which has already been adopted by the majority of neutrino experiments, including those using the JPARC and NuMI neutrino beam lines. While existing neutrino MC generators simply simulate neutrino interactions and may include the ability to use some form of user-defined neutrino flux, GENIE can analyze detector geometries written in ROOT or GEANT [10].

GENIE simulates neutrino interactions, for all neutrino flavors and all nuclear targets, over a large energy range from a few MeV to several hundred GeV. The physics models used can, broadly speaking, be split into models which describe cross-sections, hadronization, and nuclear physics. Full information on all the models and physics choices used in GENIE can be found at [1].

The neutrino-nucleon cross section model is similar to other previous approaches: Llewellyn-Smith for quasi-elastic scattering (QE) [11], Rein-Sehgal for the coherent and incoherent pion production (RES) [12, 13], and Bodek-Yang [14] for deep inelastic scattering (DIS). The single-pion and two pion channels in the transition region are tuned to match bubble chamber data. GENIE uses a homegrown hadronization model, the AGKY-model, which combines PYTHIA/JETSET at higher invariant masses with the KNO-scaling at lower invariant masses (details are given in Ref. [15]).

A Fermi-gas model with a constant Fermi momentum (221 MeV for C, 250 MeV for Fe) and constant binding energy (30 MeV) is used to describe the initial nucleons; it is modified to account for nucleon-nucleon correlations following the work of Bodek and Ritchie [16].

The rescattering of pions and nucleons is simulated with INTRANUKE/hA, an "effective" FSI model, which is anchored to a large body of experimental data, in particular π^{56}Fe and p^{56}Fe data (default model). INTRANUKE/hN is a cascade model based on nucleon cross sections. Details are given in Ref. [17].

Within the past few years, in Romania, many studies have been made to determine the neutrino properties [18, 19, 20, 21]. The analysis presented in this paper has the same purpose and was realised using a neutrino MC generator.

2. RESULTS OF SIMULATIONS FOR THE υN INTERACTIONS

In our work we used GENIE to produced similar sets of 50,000 events simulating 1 and 3.2 GeV υ_e charged-current interactions on ^{40}Ar. A primary state is defined as the topology of particles produced by the primary neutrino interaction and the final state is defined as the topology of the particles after any secondary interactions, such as intranuclear rescattering, have taken place.

We worked with this MC neutrino generator to study neutrino interactions because the programs that are simulating detector response, like GEANT, did not have a validated neutrino interaction package, so these particles have to be first generated and after that passed throw detector geometry.

Cross sections. The cross section model provides the calculation of the differential and total cross sections. During event generation, the total cross section is used together with the flux to determine the energies of interacting neutrinos. The cross sections for specific processes are then used to determine which interaction type occurs, and the differential distributions for that interaction model are used to determine the event kinematics. While the differential distributions must be calculated event-by-event, the total cross sections can be pre-calculated and stored for use by any jobs sharing the same physics models. Over this energy range 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 total υN CC scattering cross section can be considered, as discussed, for example, by Kuzmin, Lyubushkin and Naumov [22], as:

$$\sigma^{tot} = \sigma^{QEL} \oplus \sigma^{1\pi} \oplus \sigma^{2\pi} \ldots \oplus \sigma^{1K} \oplus \ldots \oplus \sigma^{DIS} . \tag{1}$$

In the absence of a model for exclusive inelastic multi-particle neutrino production, the above is usually being approximated as:

$$\sigma^{tot} = \sigma^{QEL} \oplus \sigma^{RES} \oplus \sigma^{DIS} \tag{2}$$

assuming that all exclusive low multiplicity inelastic reactions proceed primarily through resonance neutrino production. For simplicity, small contributions to the total cross section in the few GeV energy range, such as coherent and elastic υ_e scattering, were omitted from the expression above. In this picture, one should be careful in avoiding double counting the low multiplicity inelastic reaction cross sections.

For exemplification, in Fig. 1, the CC electronic neutrino cross sections divided by energy as a function of neutrino energy is presented for three type of interactions: (QE), (RES) and (DIS).

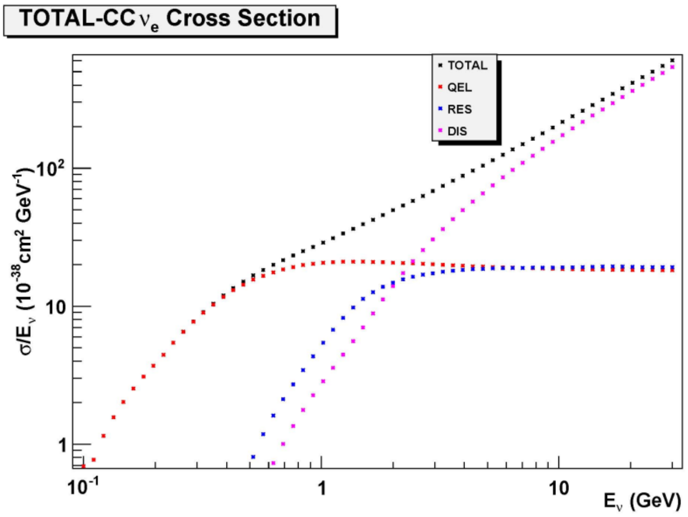

Fig. 1 – CC electronic neutrino cross section, divided by energy, as a function of neutrino energy.

Final state primary lepton. After we generated events and analyzed samples, we decided to look at the primary lepton created in the events. For electronic-neutrino interactions, the primary lepton created in the events is invariably either an electron or an electronic-neutrino. Since the neutrinos generated from events would not be seen in a detector, we restricted the primary lepton to electrons only. In Fig. 2, the energy spectrum of the primary lepton is shown for different types of event – out of all the events, roughly 20% were quasi-elastic, 32% resonance and 48% deep inelastic scattering events. It can be seen that in quasi-elastic events the lepton is more likely to have energy closer to that of the initial neutrino. In contrast, the leptons generated in resonance events have a much lower energy, since energy is required to produce the Δ resonance [23].

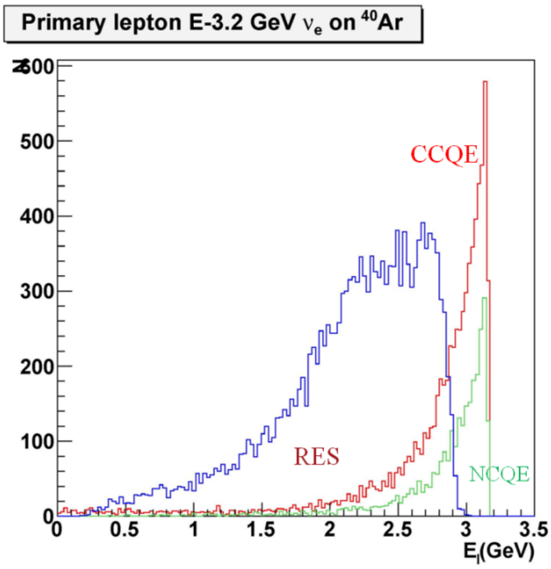

Fig. 2 – Energy spectrum for the final state primary lepton.

For υ_e on ^{40}Ar interactions around 1 GeV energy, we present the angular distribution of the electrons. Primary electrons from CCQE events are more often emitted in the initial neutrino direction and the resonance events have a more isotropic distribution, although there are still more emitted in the initial neutrino direction.

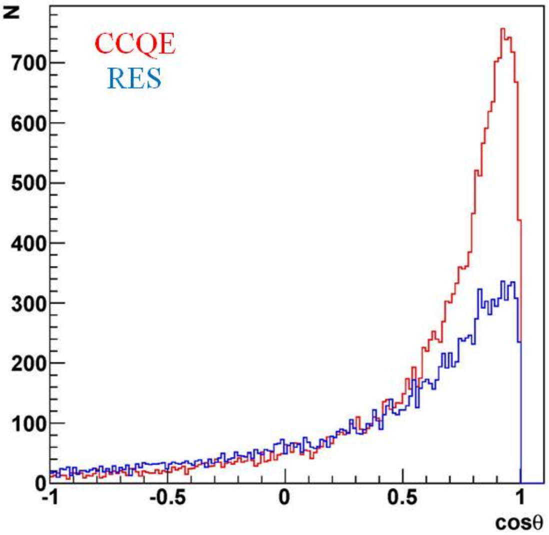

Fig. 3 – The primary electron angular spectra divided by interaction type.

Figure 4 shows a scatter graph of the primary electron energy against its angle. The CCQE and resonance events fall in two different areas. This plot highlights why CCQE events are useful for reconstructing the initial neutrino energy, as they fall along a band which relates the electrons energy with its angle. This band falls on the line given by using the CCQE reconstruction equation:

$$E_\nu = \frac{m_p E_l - \frac{1}{2} m_l^2}{m_p - E_l + p_l \cos\theta_l} \tag{3}$$

and setting $E_\nu = 1$ GeV to give a relationship between the electron energy E_l and angle θ_l. As can be seen, the CCQE events follow this relationship, with some deviation due to final state rescattering, and can therefore be used to determine the initial neutrino's energy. However, the resonance events fall in a different region with lower electron energy than CCQE events, and do not correlate with the CCQE reconstruction equation at all. Thus, if a resonance event is misidentified as a CCQE event, a major source of background in neutrino experiments, the neutrino energy will be reconstructed as a lot lower than reality. This highlights the need to understand backgrounds when using CCQE events as signal.

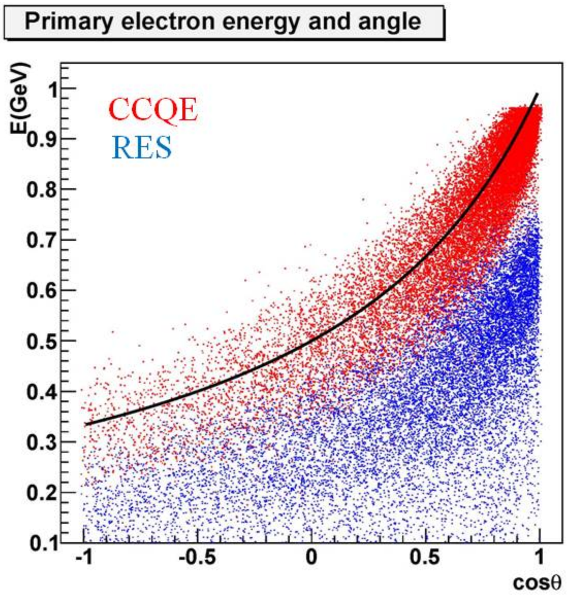

Fig. 4 – Correlation between energy and scattered angle of the primary electron.

3. SUMMARY AND POSSIBLE CONCLUSIONS

Our results have been obtained with GENIE in one particular user-defined situation: neutrino scattered on a nuclear fix target. To study neutrino-nucleus interactions in the few GeV energy region we generated a mono-energetic 1 and 3.2 GeV electronic-neutrinos interacting with an Argon-40 nucleus. The present study is useful for improving underground detectors discovery potential for determining the neutrino properties.

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REFERENCES

1. C. Andreopoulos *et al.*, [arXiv:hep-ph/0905.2517]; http://www.genie-mc.org/
2. T. Leitner, L. Alvarez-Ruso and U. Mosel, Phys. Rev., C **73**, 065502 (2006) ; GiBUU web page: http://gibuu.physik.uni-giessen.de/GiBUU/
3. G. Battistoni *et al.*, AIP Conf. Proc., 896, 31 (2007).
A. Fasso, A. Ferrari, J. Ranft, and P.R. Sala, CERN-2005-10 (2005).
4. Y. Hayato, Nucl. Phys. Proc. Suppl., **112**, 171 (2002).
5. NuWro web page: http://borg.ift.uni.wroc.pl/websvn/
6. D. Casper, Nucl. Phys. Proc. Suppl., **112**, 161 (2002).
7. R. Brun, F. Rademakers, Nucl. Instrum. Meth., **A389** 81–86 (1997).
8. *** http://hepforge.cedar.ac.uk/lhapdf/; hep-ph/0508110
9. *** Pythia 6.400 manual, JHEP, **05**, 026 (2006)
10. S. Agostinelli et al., Nucl. Inst. and Meth., **A 506**, 250–303 (2003).
11. C. H. Llewellyn Smith, Phys.Rept., **3**, 261 (1972).
12. D. Rein and L. M. Sehgal, Ann. Phys., **133**, 79 (1981).
13. D. Rein and L.M. Sehgal, Nucl. Phys., B **223**, 29 (1983).
14. A. Bodek, I. Park and U.-K. Yang, Nucl. Phys. Proc.Suppl., **139**, 113 (2005).
15. C. Andreopoulos *et al.*, arXiv:0905.2517.
16. A. Bodek and J. L. Ritchie, Phys. Rev., D **23**, 1070 (1981).
17. S. Dytman, Lectures given at 45th Karpacz Winter School in Theoretical Physics, February 2–11, 2009, La˛dek-Zdrój, Poland, http://wng.ift.uni.wroc.pl/karp45
18. A. Saftoiu *et al.*, Rom. J. Phys., **56**, 664 (2011).
19. A. M. Apostu *et al.*, Rom. Rep. Phys., **63**, 220 (2011).
20. G. Toma *et al.*, Rom. Rep. Phys., **63**, 383 (2011).
21. B. Mitrica *et al.*, Rom. Rep. Phys., **62**, 750 (2010).
22. K. S. Kuzmin, V. V. Lyubushkin, V. A. Naumov, hep-ph/0511308.
23. D. Chesneanu, AIP Conf. Proc., **1304**, 489–493 (2010)