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Mapping neutrino nuclei interactions using electrons

R. Williams, D. P. Watts, N. Zachariou, M. Bashkanov and S. Fegan

University of York - York, Y010 5DD, Heslington, UK

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Summary. — Next-generation neutrino facilities, such as DUNE, rely on precise modelling of neutrino-induced hadron knockout processes from nuclei in the detector medium (*e.g*, argon) to determine the initial (untagged) neutrino beam energy and determine the neutrino flux. However, uncertainty in the modelling of these nuclear interactions constitutes the largest systematic uncertainty in extracting key physics, including the neutrino oscillation parameters. Within the e4nu Collaboration at the Thomas Jefferson National Laboratory (JLab), we address this by studying the same knockout reactions exploited at neutrino facilities, but using incident electron beams of precisely determined energy (up to 12 GeV). A range of hadron knockout reactions from light to heavy nuclear targets are determined utilising the nearly complete acceptance of the CLAS12 spectrometer. This expansive data set will be used to benchmark nuclear calculations (GiBUU and GENIE) in the poorly constrained kinematic regime of DUNE and will directly affect the achievable accuracy for the key physics outputs of DUNE. Our current results, the first from e4nu at CLAS12, are presented and implications for neutrino facilities discussed.

1. – Introduction

Next-generation neutrino facilities, such as the Deep Underground Neutrino Facility (DUNE), will attempt to answer fundamental questions related to neutrinos. These particles interact weakly with matter and billions pass through our bodies each second. In relation to this, the theoretical description of neutrino physics is missing key ingredients to provide a complete description of the nature of their interaction, which can be provided with the utilisation of experimental facilities. Muon neutrinos are produced at Fermilab when the protons are accelerated and collide with a fixed target (a disk of pure graphite). The neutrinos produced, via decays of the product particles from the proton-target interactions, are aimed towards their final destination, the Sanford Underground Research Facility (SURF), in South Dakota situated approximately 800 miles from the location they were initially postulated. A large system of detectors, with each made up of 17000 tons of liquid argon and cooled to −184°, is used to detect these particles via nuclear interactions within the argon medium. The product particles from the neutrino-argon interactions are measured and the initial neutrino flux is then extracted [1].

Both experimental facilities and theoretical models designed for neutrino physics must coexist to provide a full understanding of these near-massless particles. Equation (1) provides a simplified description for extracting the initial neutrino flux from an experimental facility,

$$N(E_{Rec}, L) = \sum_i \Phi(E, L) \times \sigma_i(E) f_{\sigma_i}(E, E_{Rec}) \mathrm{d}E. \tag{1}$$

The counts ($N(E_{Rec}, L)$) are determined by measuring the product particles. Theoretical models are then employed to extract the initial neutrino flux ($\Phi(E, L)$) using reaction cross-sections and migration matrices ($\sigma_i(E) f_{\sigma_i}(E, E_{Rec})$), which can be used to extract the initial energy and determine neutrino oscillation parameters(1). A key issue with the extraction of the neutrino flux is the lack of accurate description for the nuclear interactions of neutrinos within the nuclear medium. This produces large systematic uncertainties when extracting neutrino oscillation parameters and improving the theoretical models will decrease the systematic uncertainty for the determination of neutrino oscillation parameters.

Currently, the two state-of-the-art neutrino models GiBUU and GENIE disagree in reaction cross-sections with each other and the experimental data. Figure 1 presents the impact that a model which does not provide an accurate description of the underlying neutrino-nucleus physics has on neutrino oscillation parameter extraction. The two models do not agree within 3σ of each other, which highlights the issues facing the theory models. If the theory of neutrino interactions was well established, these two models would not disagree to the extent highlighted.

The event generators used in this analysis can generate both neutrino and electron beams, and both neutrinos and electrons interact with a single boson exchange and via the same underlying nuclear physics. The key difference is the strength of the interactions. Electrons predominantly interact via the electromagnetic force and neutrinos interact via the weak nuclear force. Since the electromagnetic force is approximately 10^6 times stronger than the weak nuclear force, this makes electrons an ideal candidate to test and benchmark the leptonic theoretical descriptions of the models. Since both particles in question are leptons, we can use electrons to benchmark neutrino-nucleus interactions. There is a large world database for electron scattering. Electrons produced at Thomas Jefferson National Laboratory (JLab) are mono-energetic, have high intensity, and overlap with the kinematical range of DUNE. Therefore, we can provide insight on the accuracy of the available models in reconstructing the initial electron beam energy using identical methods to DUNE and other neutrino facilities. Equation (2) presents the method for reconstructing the initial electron beam energy; we combine the energy of the scattered electron ($E_{e'}$), the sum of the energy of all mesons ($\sum E_{Mesons}$), the sum of the kinetic energies of all nucleons knocked out (protons and neutrons $\sum T_{nucleons}$) and combine the average separation energy ($\approx 20\,\mathrm{MeV}$) for each nucleon knocked out ($\sum \epsilon$),

$$E_{Rec} = E_{e'} + \sum E_{Mesons} + \sum T_{nucleons} + \sum \epsilon. \tag{2}$$

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(1) Migration matrices are objects which allow us to connect the reconstructed energy to the true energy.

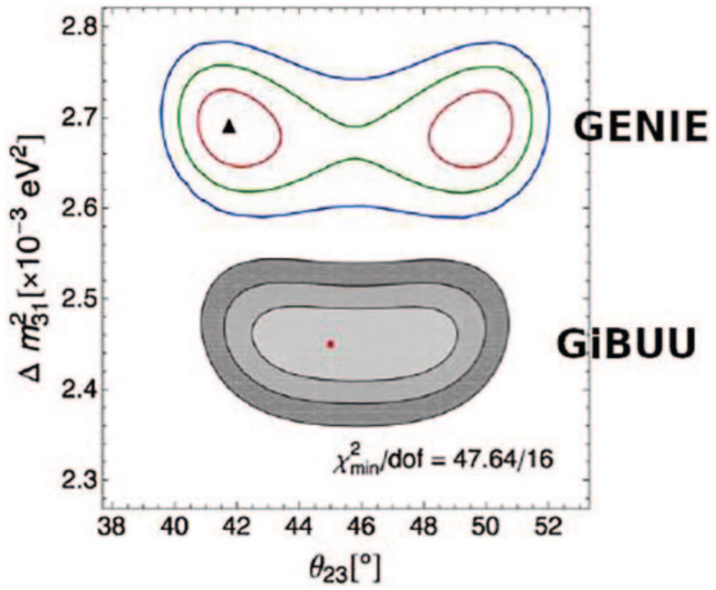

Fig. 1. – Predictions of oscillation parameters based on two neutrino-nucleus interaction models (Genie and GIBUU) [2]. The grey and coloured regions denote the confidence level (1, 2 and 3σ) of the determination of the neutrino oscillation parameters. The grey regions present the case where the data is generated and analysed with the same theoretical model (GIBUU) and the coloured regions present the case where the data was generated using GiBUU and analysed with GENIE. The red dot marks the true input value and the black triangle indicates the best fit point.

2. – Previous results

Previous results taken at JLab (shown in fig. 2) for quasielastic $(e, e'p)$ scattering on C_{12} and Fe_{56} for primary electron beam energies 2 and 4 GeV, highlighted the shortcomings of the GENIE model in attempting to replicate the behaviour of the experimental data [3].

Not only is the cross-section for the beam energy reconstruction not replicated, but the events which reconstruct to a lower energy than the beam were also not well modelled. These events typically contain unidentified particles in the final state and these are produced mainly from other nuclear interactions, other than quasielastic. The lack of reliable 1, 2 and 3π production models, including an inaccurate modelling of in-medium resonances and deep inelastic scattering (DIS), among other fundamental processes, can contribute to this mismatch between the experimental and theoretical data. Quasielastic scattering is a small part of the full description of leptonic interactions, therefore future experiments need to consider many-body interactions involving multi proton knockout, pion and kaon production channels including vector-meson production, resonances and deep inelastic scattering, among many other interactions.

3. – The RGM experiment

Data collected from JLab during the RGM experiment, which ran from October 2020 to February 2021 using the CLAS12 detector, aims to tackle many of the aforementioned

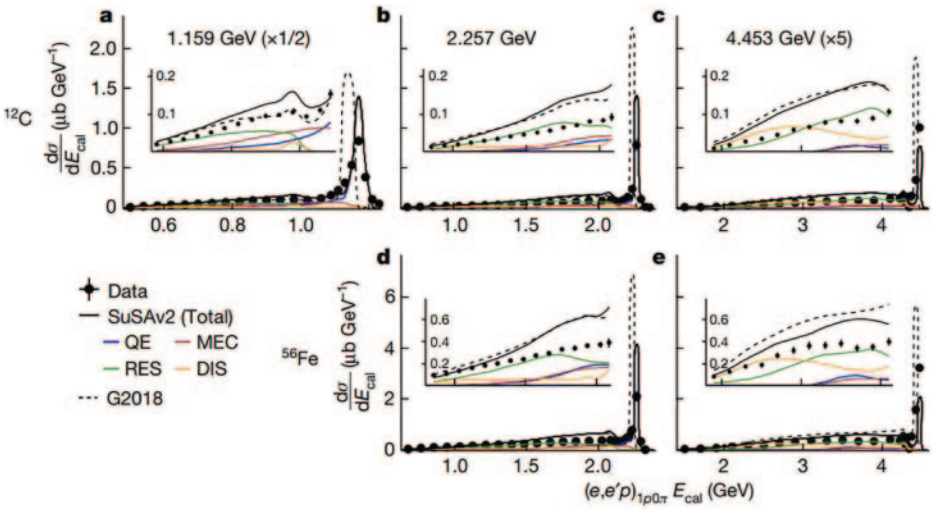

Fig. 2. – e2a data presenting quasielastic $(e, e'p)$ scattering for different beam energy settings for C_{12} and Fe_{56} targets with comparisons to the GENIE model. The GENIE model is broken down to the contributions of fundamental processes and for two different tuning settings G2018 and the newer SuSAv2 parametrisation. Panels (a) through (e) present the electron beam energy reconstruction for different beam energies for the C_{12} (top) and Fe_{56} (bottom) targets [3].

issues and constrain the theory models presented within the kinematics of DUNE. The CLAS12 detector has a nearly 4π coverage and excellent charged particle detection efficiency and tracking. Four different electron beam energies 1, 2, 4 and 6 GeV were impinged on a number of targets including D, He_4, C_{12}, Ar_{40} and Sn_{120}. Specifically, the argon target was liquid argon which allows us to obtain results with electrons that would precisely match the kinematics of neutrino interactions in DUNE.

4. – Results

The results presented in fig. 3 show the yields for the experimental data from the experiment at JLab for the deuterium target at 2 GeV and 6 GeV, showing the accuracy of the beam reconstruction method for the reaction $(e, e'p)$. The large peak near 1 GeV for the 6 GeV beam data corresponds to the radiative tail where electrons interacted down the beamline before reaching the target.

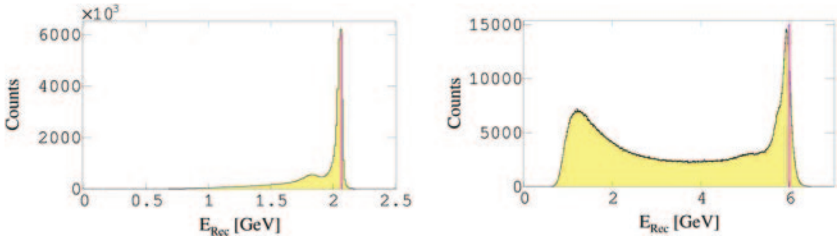

Fig. 3. – Quasielastic $(e, e'p)$ scattering from deuterium for 2 GeV (left) and 6 GeV (right) from the experimental data set, where the magenta line denotes the true beam energy.

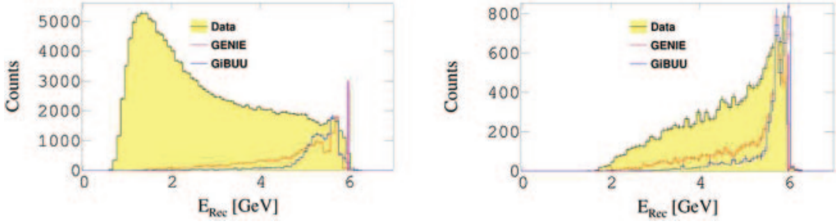

Fig. 4. – Quasielastic $(e, e'p)$ scattering (left) and $(e, e'p\pi^-)$ (right), restricted to the forward detector ($5° \leq \theta \leq 40°$), from Ar_{40} at 6 GeV from the experimental data set (yellow) with comparisons to GiBUU (blue) and GENIE (red), where the magenta line denotes the location of the true beam energy.

Figure 4 presents the experimental data alongside the GENIE and GiBUU models, after processing the generated model data through a realistic CLAS12 detector simulation for the liquid argon target at 6 GeV for the reaction $(e, e'p)$ (left) and $(e, e'p\pi^-)$ (right). The three data sets have been amplitude normalised. The reactions are determined on a semi-exclusive level; the charged particles are determined, but neutral particles are ignored. For the quasielastic reaction, the nuclear physics is insufficiently described by both models and this is clear from the under-appreciation of the background (which we expect to be present at such a level for a nuclear target with the density of argon). For the pion channel, the models provide a better description for the underlying reactions, but the strength is still too weak in both GiBUU and GENIE.

5. – Conclusion

The large disagreements between the theoretical models and the experimental data present an exciting challenge for the future. We have provided the first studies utilising data from the RGM experiment for a small selection of reaction channels. Many more reactions are currently under analysis that will allow us to underpin the modeling of dominating reactions within the state-of-the-art neutrino models. These studies from the data provide the first model comparisons at the DUNE kinematics for semi-exclusive reactions. The goal for the future is to provide a cross-section description for each reaction such that the models can be tuned, and the neutrino oscillation parameters extracted from future neutrino experiments will have a significantly smaller systematic uncertainty than previous parameter determinations.

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REFERENCES

[1] Abi B., Acciarri R. *et al.*, arXiv:2002.02967 (2020).
[2] Coloma P. *et al.*, *Phys. Rev. D*, **89** (2014) 073015.
[3] Khachatryan M., Papadopoulou A. *et al.*, *Nature*, **599** (2021) 565.