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Future of Neutrino Interaction Models

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Abstract. Neutrino-nucleus cross sections are one of the dominant sources of systematic errors in long-baseline neutrino oscillation experiments. To achieve the goals of precision measurements of the mixing angles and difference of the mass eigenstates squared, and discover the mass hierarchy and CP-violating phase, the underlying neutrino interactions must be better understood. This poster will mention some recent improvements in models in the interaction generators as well as some possible future improvements for proposed experiments.

1. Introduction

Long-baseline neutrino oscillation [1, 2, 3] and neutrino-nucleus scattering [4, 5] experiments have found consistent discrepancies between data and the models used in their interaction generators in the region where $E_\nu = 1\,\text{GeV}$ and between themselves. These differences contribute large systematic errors related to the neutrino cross section, and may introduce a bias in the best-fit parameters of an oscillation analysis if at least one of the interactions is being mis-modeled or is missing entirely. This paper will give a brief overview of some of the current data-model discrepancies, highlight the charged current (CC) quasi-elastic (QE) model as a source of possible improvements, and then look to the future of being able to describe describe data from current and future experiments with an eye to improving the predictions.

2. Typical Models in Neutrino Generators

A typical neutrino interaction generator, such as GENIE [6] or NEUT [7], has a base set of models to describe various interactions between a neutrino and a nuclear target. These include charged and neutral current (quasi-)elastic scattering, resonant production and decay to form single meson or photon states, coherent pion production, and deep inelastic scattering. There is also a hadron transport model used for hadrons created by an interaction in a nucleus attempting to escape, which can affect both the number and type of particles in the final state and their final outgoing momenta.

In slightly more detail, a typical model used for CCQE interactions is one developed by Llewellyn-Smith [8] in the target nucleon rest frame, with the differential cross section being:

$$\frac{d\sigma^{\nu,\overline{\nu}}}{dQ^2} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2} \times \left[A(Q^2) \mp \frac{(s-u)B(Q^2)}{M^2} + \frac{(s-u)^2 C(Q^2)}{M^4} \right], \tag{1}$$

where M is the target nucleon mass; s and u are Mandelstam variables; the -(+) sign is for (anti)neutrinos; Q^2 is non-negative; and A, B, and C are terms containing the vector form

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factors F_1 and F_2, pseudo vector form factor F_P, and axial form factor F_A. The axial form factor normally takes the form as a dipole

$$F_A\left(Q^2\right) = \frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2}, \tag{2}$$

where g_A is a constant measured beta decay experiments and has a value of -1.267 and M_A is the axial mass. Assuming Equation 2 is the way Nature describes the axial form factor, the axial mass should have the same value in all experiments where it is measured. Values derived from pion scattering experiments and deuterium bubble chamber experiments indicate the axial mass should have a value slightly larger than $1\,\mathrm{GeV/c^2}$ with only a few-% error, e.g. $1.016\pm0.026\,\mathrm{GeV/c^2}$ [9] extracted from deuterium.

3. Discrepancies Between Data and Models

Recent cross section measurements in various neutrino experiments have highlighted some discrepancies between the interaction models and their data sets and also between experiments. For CCQE interactions, the MiniBooNE (MB) [3] and NOMAD [10] experiments measure different values of M_A, with MB reporting a central value of $M_A = 1.35\,\mathrm{GeV/c^2}$ [11] and NOMAD $M_A = 1.05\,\mathrm{GeV/c^2}$ [12].

Inclusive single pion measurements have other differences. For inclusive neutral current single π^0 measurements, the momentum spectrum for K2K [13] and MB [14] both have different shapes than the model prediction. The MB CC single pion measurements (one where the only meson is a π^+ in the final state [15], the other only a π^0 [16]) both have a shape and normalization discrepancy. Recently, MINERνA's results for CC single charged pion interactions have indicated that the default interaction models agree with their data with no significant modifications needed (this has yet to be published at the time of writing).

4. Sources of Discrepancies

The reason for these data-model discrepancies, as well as differences between experiments, is multi-fold. One source stems from the fact that most current experiments have mean neutrino energies around 1 GeV, which means lower momentum particles that have more time to interact in the nuclear environment. This implies the hadron transport models as well as the simulation of the overall nuclear density need to be treated more carefully within whatever framework is being used.

The nuclear environment also makes it so it is possible the models used in the generators are not complete. Due to the MB CCQE measurement, it has been proposed that there is a contribution from multi-nucleon interactions. Simplistically, the gauge boson is interacting with at least two nucleons, rather than one. This can be seen in models by Nieves *et al.* [17] and Martini *et al.* [18].

Finally, there is the problem of definition. Experiments and models must be clear when they use a term like CCQE due to the fact that this could mean among other things:

- $\nu_\mu + n \rightarrow \mu + p$: generator definition before intranuclear effects occur
- $\nu_\mu + X \rightarrow \mu + X' + 0$ mesons: MB's definition, where X' allows for any number of nucleons
- $\nu_\mu + X \rightarrow \mu + X' + 0$ mesons+no vertex activity: this would be a possible selection in a plastic scintillating detector
- $\nu_\mu + X \rightarrow \mu + 1p + X' + 0\pi$: NOMAD's definition

If two experiments are using the same definition, it may be easier to compare their results. Otherwise, the model needs to take these into account for cross comparisons to see if any differences possibly have the same underlying source.

5. Possible Future Improvements

The necessary improvements to the cross section models comes from the necessary dialogue between theorists, experimentalists, and phenomenologists. Since CCQE-like events (mostly interactions with a single muon and no mesons visible in the detector) have multi-nucleon contributions, being able to implement these models in a generator becomes necessary. Some steps have been taken towards this, but there needs to be an agreed-upon framework so that it becomes easy to include new models of the same phenomenon in a generator setting to test against data. Models that produce resonances are being retuned based on available data and updates to their form factors [19]. In both cases, pion-nucleon scattering measurements becomes more and more important to be able to see how we can arrive at the visible final states observed in experiment. Additionally, electron scattering data can give greater constraints on vector current form factors, helping reduce the possible parameters that can be varied in a model.

With some future very long-baseline experiments, e.g. LBNE, needing a higher neutrino energy to maximize the effect of oscillations, more attention needs to be paid to hadronization multiplicities and improving the predictions for DIS in the low-Q^2, low-W region of the interaction parameters space. Some work can be seen for improving the DIS predictions in reference [20].

While these can be done on the theory and phenomenology side of things for the generators, the community needs additional measurements made on a variety of targets across different energies. This will allow to see how the models react to data with different interactions contributing, as well as seeing how much the target affects a model's predictive power. Ideally, this would include targets from deuterium through lead, at the least, with the main focus being on carbon, oxygen, argon, and iron, since they are the most common targets used in neutrino physics. Of course, the data from these measurements also needs to be released in a way where it is possible to test any models that already exist in the generators and tune any parameters that the models allow, while also checking for consistency.

In all cases, none of these ideas are new to the community, but the hard work is making it happen on a reasonable time scale, all the while being able to react to new publications while we try to get a better handle on what Nature is telling us.

References

[1] Ahn M *et al.* (K2K Collaboration) 2006 *Phys.Rev.* **D74** 072003 (*Preprint* hep-ex/0606032)
[2] Abe K *et al.* (T2K Collaboration) 2011 *Nucl.Instrum.Meth.* **A659** 106–135 (*Preprint* 1106.1238)
[3] Aguilar-Arevalo A *et al.* (MiniBooNE Collaboration) 2009 *Nucl.Instrum.Meth.* **A599** 28–46 (*Preprint* 0806.4201)
[4] Aliaga L *et al.* (MINERvA Collaboration) 2014 *Nucl.Instrum.Meth.* **A743** 130–159 (*Preprint* 1305.5199)
[5] Aguilar-Arevalo A *et al.* (SciBooNE Collaboration) 2006 (*Preprint* hep-ex/0601022)
[6] Andreopoulos C *et al.* 2010 *Nucl. Instrum. Meth.* **A614** 87–104 (*Preprint* 0905.2517)
[7] Hayato Y 2009 *Acta Phys.Polon.* **B40** 2477–2489
[8] Llewellyn-Smith C H 1972 *Phys. Rep.* **3**(5) 261–379
[9] Bodek A, Avvakumov S, Bradford R and Budd H S 2008 *Eur.Phys.J.* **C53** 349–354 (*Preprint* 0708.1946)
[10] Altegoer J *et al.* (NOMAD) 1998 *Nucl. Instrum. Meth.* **A404** 96–128
[11] Aguilar-Arevalo A *et al.* (MiniBooNE Collaboration) 2010 *Phys.Rev.* **D81** 092005 (*Preprint* 1002.2680)
[12] Lyubushkin V *et al.* (NOMAD Collaboration) 2009 *Eur.Phys.J.* **C63** 355–381 (*Preprint* 0812.4543)
[13] Nakayama S *et al.* (K2K Collaboration) 2005 *Phys.Lett.* **B619** 255–262 (*Preprint* hep-ex/0408134)
[14] Aguilar-Arevalo A A *et al.* (MiniBooNE Collaboration) 2010 *Phys.Rev.* **D81** 013005 (*Preprint* 0911.2063)
[15] Aguilar-Arevalo A *et al.* (MiniBooNE Collaboration) 2011 *Phys.Rev.* **D83** 052007 (*Preprint* 1011.3572)
[16] Aguilar-Arevalo A *et al.* (MiniBooNE Collaboration) 2011 *Phys.Rev.* **D83** 052009 (*Preprint* 1010.3264)
[17] Nieves J, Simo I R and Vacas M J V 2011 *Phys. Rev. C* **83**(4) 045501
[18] Martini M, Ericson M, Chanfray G and Marteau J 2009 *Phys.Rev.* **C80** 065501 (*Preprint* 0910.2622)
[19] Graczyk K M and Sobczyk J T 2008 *Phys.Rev.* **D77** 053001 (*Preprint* 0707.3561)
[20] Morfin J G 2013 *J.Phys.Conf.Ser.* **408** 012054