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Discrimination of parametrizations for nuclear effects in neutrino scattering through comparisons of low ($\sim$ 700 MeV) and medium ($\sim$ 3 GeV) energy cross-section data

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High-quality charged current quasielastic scattering data have recently been reported for both muon neutrinos and antineutrinos from several accelerator-based neutrino experiments. Measurements from MiniBooNE were the first to indicate that more complex nuclear effects, now thought to be the result of nucleon pair correlations, may contribute to neutrino quasielastic samples at a much higher significance than previously assumed. These findings are now being tested by MINERνA and other contemporary neutrino experiments. Presented here is a comparison of data from MiniBooNE and MINERνA to a few example parametrizations of these nuclear effects. It has been demonstrated that such effects may bias future measurements of neutrino oscillation parameters and so this issue continues to press the neutrino community. A comparison of data over a large range of neutrino energies is one approach to exploring the extent to which such nucleon correlations may influence our understanding and subsequent modeling of neutrino quasielastic scattering.

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Charged current quasielastic scattering (CCQE, $\nu_l + N \rightarrow l + N'$) is the dominant interaction channel in many neutrino oscillation measurements. In practice, the assumed simple multiplicity and topology of such processes allow for the recovery of the incident neutrino energy (an essential quantity in neutrino oscillation fits) using only measurement of the outgoing charged lepton. Assuming background processes can be reliably subtracted with adequate precision, such CCQE samples then become an attractive channel through which to extract oscillation parameters because the sole reliance on lepton kinematics avoids experimental complications associated with the need to explicitly reconstruct final state nucleons.

Recently, there has been mounting evidence to suggest that such CCQE processes may not be as simple as originally thought, particularly when scattering off nuclear targets [1]. The presence of correlated nucleon pairs in the nuclear environment may alter both the magnitude and kinematics of these interactions at a significant level. Resultant enhancements have been previously observed in transverse electron-nucleus data [2], but the role such effects play is only now being appreciated in the context of neutrino-nucleus scattering, in large part motivated by the MiniBooNE data [3, 4].

Of course, it is important to get the physics right. The complex nuclear environment can have a potentially large impact on the determination of neutrino energy, (anti)neutrino rates, and nucleon emission in neutrino oscillation analyses [5–7]. Hence, much attention has been devoted to this topic in recent years. While the theoretical and experimental understanding of this issue is still taking shape, most neutrino experiments do not currently include a complete implementation of nuclear effects (including nucleon correlations) in their simulations. Lacking this, confrontation of the experimental data and leading models have often been limited to comparisons of the absolute cross section as a function of neutrino energy, E_ν, and hence suffer from model dependences inherent in extracting E_ν from the data. High statistics information from MiniBooNE has recently changed this and allowed detailed comparison of nuclear models to flux-averaged double differential distributions of the observed muon kinematics, available for the first time for both neutrino and antineutrino quasielastic scattering on carbon [3, 4]. Furthermore, the full angular coverage of the final state muon offered by the spherically-symmetric detector allows a unique test of the transverse enhancement expected due to nucleon pair correlations (such effects are expected to be largest for backwards-scattered muons relative to the incoming neutrino beam).

More recently, MINERνA has reported measurements of the flux-averaged differential cross section, $d\sigma/dQ^2_{QE}$, for both neutrino and antineutrino quasielastic scattering also on a carbon-based target [8, 9]. The analysis of the MINERνA data further includes an exploitation of it's fine-grained calorimetry to scrutinize hadronic activity near the quasielastic interaction vertex. Like the earlier MiniBooNE findings, the results suggest the presence of nuclear effects not included in widely-used relativistic Fermi Gas (RFG) [10] models which assume independent (and not correlated) nucleons in the nucleus. To facilitate a more direct comparison of the MiniBooNE and MINERνA data, we present a recasting of the MiniBooNE experimental data in the same form as recently reported by MINERνA [11].

Here, the exercise of producing normalized ratios in Q^2_{QE} with respect to the nominal RFG model, as pre-

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sented by MINERνA, is repeated with the MiniBooNE neutrino and antineutrino quasielastic data. In this case, Q^2_{QE} refers to the squared four-momentum transfer obtained using only reconstructed muon kinematics and assuming quasielastic scattering with a single target nucleon at rest:

$$E_\nu^{QE} = \frac{2(M'_n)E_\mu - ((M'_n)^2 + m_\mu^2 - M_p^2)}{2\cdot[(M'_n) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu]}, \quad (1)$$

$$Q^2_{QE} = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu), \quad (2)$$

where $E_\mu = T_\mu + m_\mu$ is the total muon energy and M_n, M_p, m_μ are the neutron, proton, and muon masses. The adjusted neutron mass, $M'_n = M_n - E_B$, depends on the separation energy in carbon, E_B, which is set to 34 (30) MeV for neutrino (antineutrino) scattering.

The results are presented in Figure 1. In following what was reported by MINERνA [8, 9, 11], a comparison is shown for two example alternatives: increasing the axial mass parameter, M_A, in the RFG model and including a parametrization of the transverse enhancement seen in electron-nucleus scattering. Both have been motivated by the MiniBooNE observations and are shown to provide viable descriptions of this data. The value for M_A is chosen from spectral fits to the MiniBooNE CCQE events [3] while electron scattering data on heavy nuclei provide the formulation of the Transverse Enhancement Model (TEM). In this implementation, the TEM specifically modifies the magnetic form factor for bound nucleons to achieve simultaneous agreement both with a wide range of electron scattering data and the early neutrino cross-section measurements on deuterium [12]. In the absence of a full nuclear physics description in neutrino event generators, such parametrizations can be a helpful tool for testing the gross features of such contributions and comparing data sets.

As for all models based on the impulse approximation, precision is not expected from the RFG in the region of small Q^2 [13]. For this reason, we focus on the higher Q^2 data and normalize the MiniBooNE distributions using the region $Q^2_{QE} > 0.2$ GeV^2. To mitigate possible misinterpretations of these results due to the use of different neutrino interaction generators, the parametrizations of nuclear effects shown here are provided by the same NuWro neutrino event generator [14] as used in the published MINERνA results.

Both increases to the axial mass and the inclusion of transverse enhancement effects have been suggested as options to describe the MiniBooNE data. As seen in Fig. 1, in general these adjustments seem to perform equally well. There seems to be some mild tension at high Q^2_{QE} between the TEM and the MiniBooNE ν_μ data; this has also been observed in comparisons of the model-independent double-differential distribution [15]. Because the two effects can lead to similar results at these neutrino energies, it can be difficult to disentangle their contributions. However, when confronting

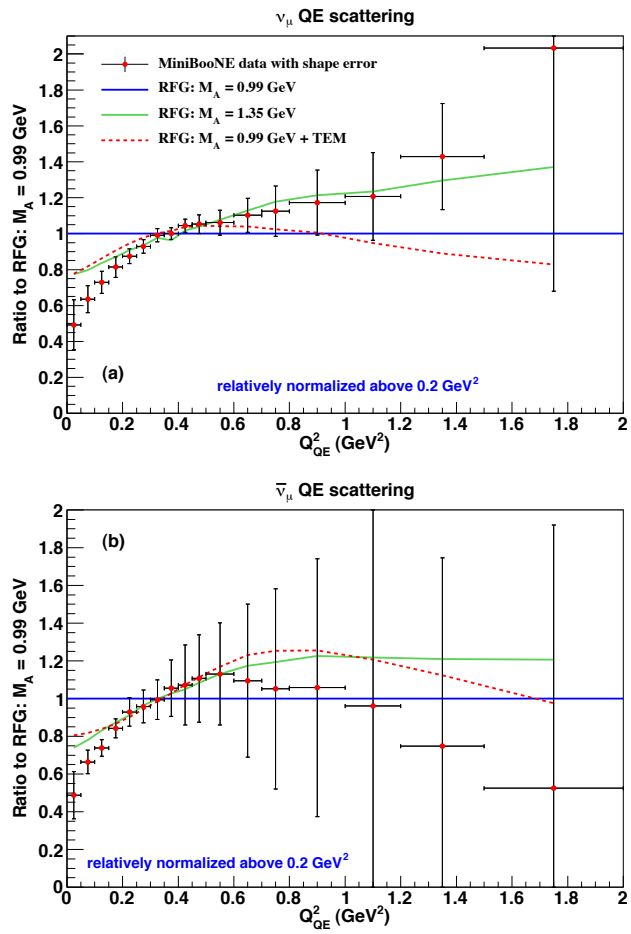

FIG. 1: (Color online) The shape of (a) ν_μ and (b) $\bar{\nu}_\mu$ MiniBooNE Q^2_{QE} data compared to parametrizations of the RFG presented in the same form as MINERνA data in recent publications [8, 9, 11]. Within the experimental uncertainty, in the MiniBooNE energy range the effect of treating nuclear effects with an increase in the axial mass is largely consistent with the TEM description. Note that Pauli blocking has not been tuned in the models shown here, and so the agreement in the low Q^2_{QE} region is somewhat worse compared to the tuned distributions shown in Refs. [3] and [4].

these MiniBooNE plots with the similar version from MINERνA [11], the benefit of comparing data sets across very different neutrino energy ranges is immediately apparent. While the changes associated with an increase in the axial mass and the inclusion of transverse enhancement effects (according to the TEM) have very similar effects at low MiniBooNE energies ($0.4 < E_\nu < 2$ GeV), the differences are much larger for higher MINERνA energies ($1.5 < E_\nu < 10$ GeV) where the two effects start to pull apart. In the case of MINERνA, a large increase in M_A is not supported by the data and the TEM is more strongly favored [11]. Separating such nuclear effects from changes to the axial-vector form factor is important given that the two choices have very different

implications for the interpretation of neutrino oscillation data.

The recent reports of the MINERνA and MiniBooNE CCQE data significantly extend the experimental knowledge of neutrino and antineutrino interactions on carbon nuclei. This robust collection of data offers an opportunity to directly test parametrizations of nuclear effects with neutrinos and antineutrinos across energy regimes crucial for current and next-generation oscillation experiments.

It will be interesting to repeat similar cross-comparisons with more sophisticated nuclear models such as microscopic calculations of multi-nucleon knock-out mechanisms [16, 17]. An issue common to many such models is that they are reliable at neutrino energies relevant to MiniBooNE but not MINERvA [18]. Moreover, implementation of such models in Monte Carlo simulation requires the consistent inclusion of RPA effects, which leads to a considerably more complicated simulation scheme compared to present designs.

It will be with these sorts of high-resolution observations of both leptonic and hadronic activity in CCQE-like interactions, along with model-independent comparisons such as those presented here, that the neutrino interaction community will arrive at a definitive resolution to the size and kinematics of these important nuclear effects and what remaining role the axial-vector form factor plays. New data and improved analyses from the MiniBooNE, MINERνA, SciBooNE [19], MicroBooNE [20], ArgoNeuT [21], ICARUS [22], NOMAD [23] and the near detectors of the T2K [24], NOνA [25] and MINOS [26] experiments are expected to play vital roles in this campaign. Meanwhile, the continued aggressive theoretical progress and anticipated integration into neutrino generators used by experiments will be invaluable towards understanding the fundamental basis for these interactions.

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