PROCEEDINGS OF SCIENCE

Non-trivial differences between charged current ν_e and ν_μ induced interactions with nuclei

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The difference between electron and muon neutrino charged-current cross sections has attracted quite some interest over the past few years. This interest is guided by the experimental effort that aims at measuring the CP-violating phase by looking for electron (anti-)neutrino appearance in (anti-)muon neutrino beams [1]. In long-baseline experiments such as T2K, models for the neutrino cross section are often constrained by near-detector data, with a muon neutrino flux that is unoscillated. Non-trivial differences between electron and muon neutrino cross sections are currently experimentally not well constrained, and different models give varying results, especially in kinematic regions where nuclear structure details become important, i.e. for low energy and momentum transfers [2, 3]. In this work we present the nuclear response and cross section using different nuclear models, for forward lepton scattering in the region of E_ν of a couple 100 MeVs. In this kinematic region the cross section is sensitive to nuclear structure details which are not accounted for in simplified models such as the relativistic Fermi gas (RFG) which is commonly used in the experimental analyses. The results show that it is important for current and future accelerator-based experiments, notably T2K [1] and the short-baseline oscillation program (i.e the MicroBooNE, SBND and ICARUS experiments) which are sensitive to the several 100 MeV region, to take nuclear structure details into account in their analyses.

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1. Modeling charged-current neutrino nucleus scattering

We compute the charged-current neutrino-nucleus cross section of neutrinos of a couple of 100 MeV with different approaches. The inclusive cross section differential in the outgoing charged lepton energy E_l and scattering angle θ_l is

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}E_l \mathrm{d}\cos\theta_l} = (G_F \cos\theta_c)^2 \frac{2E_l k_l}{f_{rec}} (v_{CC}R_{CC} - 2v_{CL}R_{CL} + v_{LL}R_L L + v_{TT}R_{TT} + h2v_{TT'}R_{TT'}), \quad (1.1)$$

with G_F the Fermi coupling constant and θ_c the Cabibbo angle, h is the helicity of the neutrino. The kinematic v-factors are the result of evaluating the lepton current with plane waves, explicit expressions for the leptonic prefactors and nuclear responses are given in e.g. [4]. All models we consider adopt the impulse approximation, in which the nuclear current is reduced to a sum of interactions with single nucleon states. We now briefly review the ingredients of the different nuclear models used.

- In the relativistic mean field (RMF) approach, the initial states are obtained as bound-states in the extended non-linear sigma-omega model [5]. The initial states occupy single-particle orbitals with well-defined energies and angular quantum numbers κ and m_J. The final-state wavefunctions with asymptotic momentum p_N are computed by solving the radial Dirac equation for every partial wave with the same scalar and vector potentials as the initial state. Recent comparisons to electron and neutrino scattering data are presented in Refs. [6, 7].
- In the Hartree-Fock (HF) model the standard non-relativistic reduction of the nuclear current is used [8], where the relativistic corrections discussed in Ref. [9] are implemented. In the HF model the bound states are obtained in a self-consistent Hartree-Fock calculation using an extended Skyrme force for the nucleon-nucleon interaction [10]. The final state wavefunctions are scattering states in the same central potential as the initial states. This model is then extended with collective excitations of the nucleus in the continuum random phase approximation (CRPA) [4]. For low momentum transfers long-range correlations, which are not accounted for in the mean-field picture, contribute to the cross section in the form of collective resonances.

It is important to note that although both approaches use different treatments for the hadronic current, in either model the final states are always energy-eigenstates of the potential used for the initial state. By this consistent treatment of all single particle states Pauli-blocking is accounted for, as the scattering wave functions do not overlap with the bound states. This is in contrast to approaches in which the final states are plane waves, while the initial state is obtained in a potential, *e.g* the relativistic plane wave impulse approximation (RPWIA). To show the effect of orthogonality the Pauli-blocked RPWIA (PB-RPWIA) was introduced in Ref. [6] where a plane wave for the knocked out nucleon is orthogonalized with respect to the bound states of the potential. In Ref. [11] it was shown that in the region of low energy and momentum transfer the ratio of ν_μ to ν_e induced cross sections is larger than one when initial and final states are treated consistently. This ratio was recovered when spurious non-orthogonal contributions to the nuclear current are eliminated in the PB-RPWIA. Here we will show the nuclear responses for the vector current, and highlight the importance of consistent initial and final state wavefunctions in order to obtain vector current conservation and the dominance of ν_μ to ν_e induced cross sections at low energy and momentum transfer.

2. Results

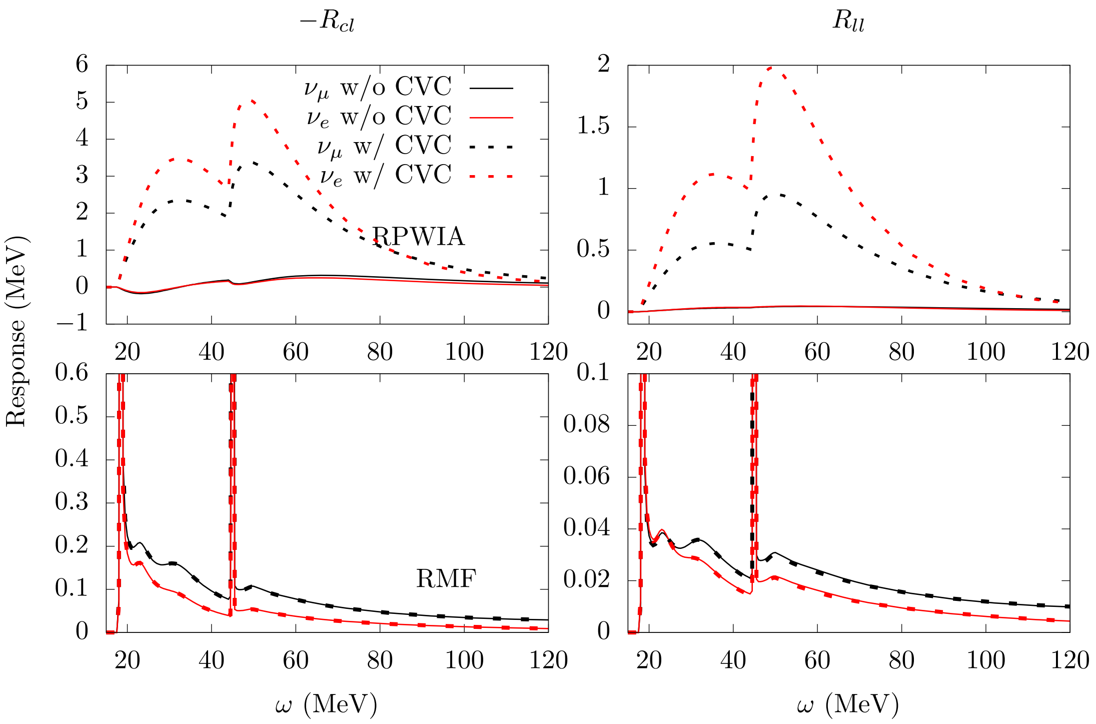

Figure 1: The CL and LL responses obtained with the vector current in the RMF (bottom) and RPWIA (top panels) approaches. The dashed line represents the response in which $J^3 = \frac{\omega}{q}J^0$ is used explicitly, while the solid lines are obtained by explicitly evaluating the third component of the current. The neutrino energy is 250 MeV and the lepton scattering angle is 10 degrees.

The conservation of the vector current, in the reference system where the momentum transfer is along the z-axis can be expressed as

$$Q_\mu J^\mu = \omega J^0 - qJ^3 = 0. \tag{2.1}$$

This means that the longitudinal responses (R_{CC}, R_{CL}, R_{LL}) can be expressed by only one component of the nuclear current. A common approach is to set $J^3 = \frac{\omega}{q}J^0$ to impose current conservation by hand. In Fig. 1 we show the effect of this procedure in the CL and LL responses in both the RMF and the RPWIA approaches. In the RMF, the response is identical whether the third component of the nuclear current is obtained either by explicitly evaluating the transition operator, or when it is obtained from the timelike component. In the RPWIA approach large variations arise, because inconsistent initial and final states are used and the current is not exactly conserved as in the RMF approach.

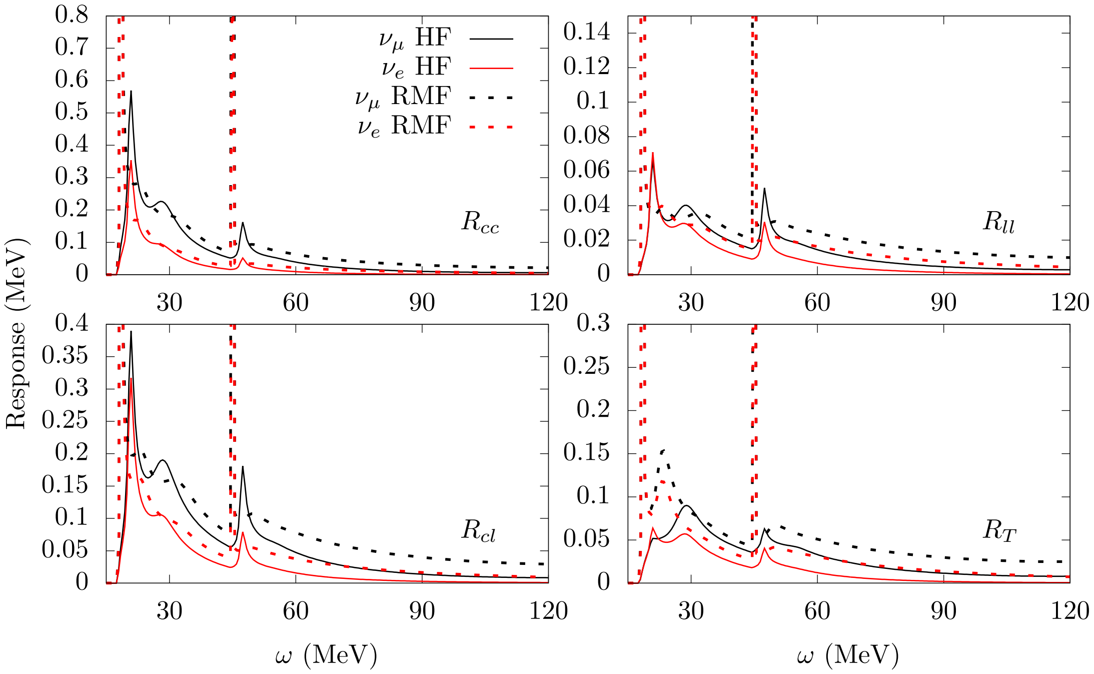

Figure 2: The vector current responses for ν_e and ν_μ in the RMF and HF on carbon with an incoming neutrino energy $E_\nu = 250$ MeV and $\theta_l = 10$ degrees.

In Fig. 2, the four responses obtained in the RMF and HF approaches are depicted, the agreement between both approaches is remarkable and the dominance of the ν_μ over ν_e induced responses for forward lepton scattering is seen in both approaches.

Finally in Fig. 3, we show the cross section in terms of the outgoing charged leptons energy, for scattering angles below 60 degrees, in the RFG and the CRPA approaches. While due to the larger available phase space the ν_e cross section is indeed larger when considering this angular region, the ν_e/ν_μ ratio is larger in the RFG approach. More important however is the difference between the energy dependence of the cross sections, the CRPA predicts a much larger cross section for leptons with higher energies than the RFG, in which the low-ω region is strongly depleted by the way Pauli-blocking is treated in an RFG approach. The effect on reconstructed neutrino energy distributions of both these approaches was shown in [8]. Considering a typical experimental situation in which the detection threshold for charged leptons is around 200 MeV one sees that the RFG severely underpredicts the cross section in this kinematic region, and that taking nuclear structure details into account could be crucial for the next generation of short baseline oscillation experiments that aim to further elucidate the excess of electron-like interactions found in the MiniBooNE experiment [12].

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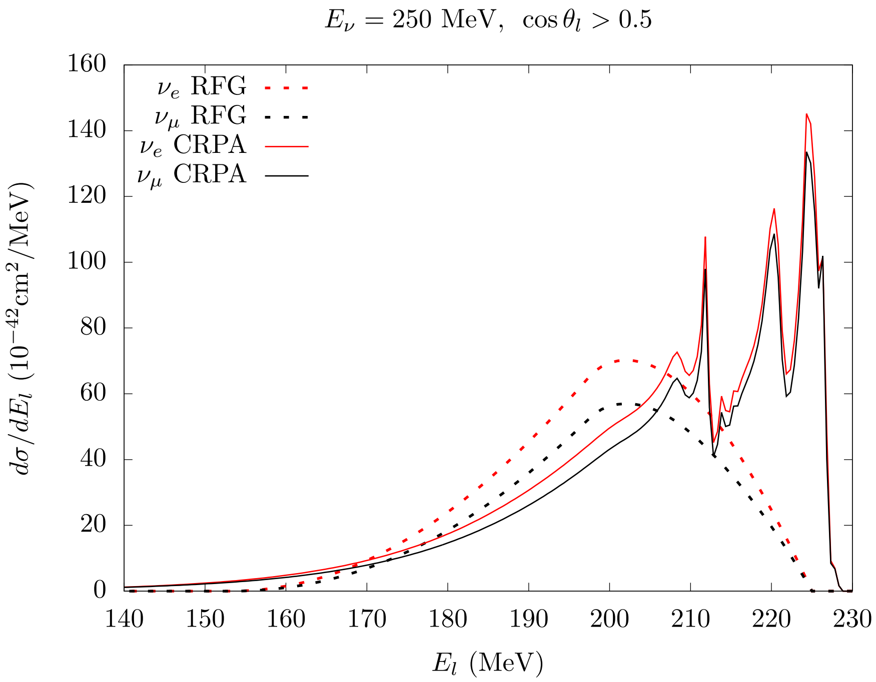

Figure 3: The CC scattering cross section of ν_e and ν_μ on carbon computed in the CRPA approach, and with the RFG with a Fermi momentum $k_F = 228$ MeV and energy shift $E_B = 25$ MeV

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References

[1] T2K Collaboration, *Phys. Rev. Lett.* **121** (2018) 171802, [`1807.07891`].

[2] M. Martini, N. Jachowicz, M. Ericson, V. Pandey, T. Van Cuyck and N. Van Dessel, *Phys. Rev. C* **94** (2016) 015501, [`1602.00230`].

[3] A. M. Ankowski, *Phys. Rev. C* **96** (2017) 035501, [`1707.01014`].

[4] V. Pandey, N. Jachowicz, T. Van Cuyck, J. Ryckebusch and M. Martini, *Phys. Rev. C* **92** (2015) 024606, [`1412.4624`].

[5] M. Sharma, M. Nagarajan and P. Ring, *Physics Letters B* **312** (1993) 377 .

[6] R. González-Jiménez, A. Nikolakopoulos, N. Jachowicz and J. M. Udías, *Phys. Rev. C* **100** (2019) 045501, [`1904.10696`].

[7] R. González-Jiménez, M. B. Barbaro, J. A. Caballero, T. W. Donnelly, N. Jachowicz, G. D. Megias et al., [`1909.07497`].

[8] N. Jachowicz, N. Van Dessel and A. Nikolakopoulos, *Journal of Physics G: Nuclear and Particle Physics* **46** (2019) 084003, [`1906.08191`].

[9] S. Jeschonnek and T. W. Donnelly, *Phys. Rev. C* **57** (1998) 2438.

[10] M. Waroquier, K. Heyde and G. Wenes, *Nuclear Physics A* **404** (1983) 269 .

[11] A. Nikolakopoulos, N. Jachowicz, N. Van Dessel, K. Niewczas, R. González-Jiménez, J. M. Udías et al., *Phys. Rev. Lett.* **123** (2019) 052501 [`1901.08050`].

[12] MiniBooNE Collaboration, *Phys. Rev. Lett.* **121** (2018) 221801, [`1805.12028`].