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How different can the ν_μ and ν_e cross sections be?

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The long-baseline neutrino-oscillation experiments of next generation aim to measure with unprecedented precision the asymmetry between appearance of electron neutrinos and antineutrinos. This goal requires the differences between the cross sections for muon and electron neutrinos to be accurately accounted for. Here I present to what extend nuclear effects affect in the same way the total cross sections of muon and electron neutrinos for charged-current scattering on carbon, and describe recent findings for the double differential cross sections.

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The main goal of the next generation of neutrino-oscillation experiments is to measure the Dirac phase, δ_{CP}. To perform such a measurement, it is necessary to extract the oscillation probabilities from the collected ν_e (and $\bar{\nu}_e$) event distributions, relying on the knowledge of the cross sections for electron neutrinos. As a consequence, the smaller the associated uncertainties, the more precise the extracted δ_{CP} value.

For example, in the case of the Deep Underground Neutrino Experiment (DUNE), 5σ sensitivity to 50% of δ_{CP} values corresponds to the exposure of $\sim$775 kt$\cdot$MW$\cdot$years when the ν_e to ν_μ total cross sections' ratio, $\sigma(\nu_e)/\sigma(\nu_\mu)$, is known with 3% uncertainty. However, this figure decreases to $\sim$480 kt$\cdot$MW$\cdot$years when $\sigma(\nu_e)/\sigma(\nu_\mu)$ is known to 1%, see Fig. 3.23 in Ref. [1]. Therefore, to maximize the scientific outcome of the oscillation experiments, the neutrino community should push for a precise estimate of the ν_e cross sections.

Unlike those for ν_μ's, the cross sections for ν_e's cannot be precisely measured in the near detectors of long-baseline experiments, due to the event statistics lower by 2 orders of magnitude, and much higher uncertainties related to the flux and the detector response than in the case of muon neutrinos. A measurement of the ν_e cross sections with 1% uncertainty seems to require constructing a dedicated facility realizing a novel approach to neutrino beams, see e.g. Refs. [2, 3].

On the other hand, on theoretical grounds, the dependence of the cross sections on the charged-lepton's mass is well known. Should one be able to derive an accurate estimate of the ν_μ cross sections without any fudge factors, the ν_e results could be calculated with the same precision.

While radiative corrections may significantly affect $\sigma(\nu_e)/\sigma(\nu_\mu)$, as shown for free nucleons [4] and for the local Fermi gas model [5], one needs to bear in mind that they are QED effects and, as such, can be calculated with the desired precision by the theoretical community.

Here I discuss how nuclear effects modify the cross sections' ratio, considering charged-current (CC) quasielastic (QE) scattering off carbon [7]. Figure 1 presents the results obtained for neutrinos and antineutrinos within the spectral function (SF) approach [6] and the global relativistic Fermi gas (RFG) model. The ratios for interactions with free nucleons are also given for comparison. As shown in Figs. 1(a) and 1(b), at energies between 1 and 5 GeV, the cross section's ratios differs from unity at 1% level, both for neutrinos and antineutrinos scattering off carbon. While the absolute cross sections obtained in the RFG model are higher by up to $\sim$11% than the calculations in the SF approach, these two very different descriptions of nuclear effects turn out to yield very consistent results for $\sigma(\nu_e)/\sigma(\nu_\mu)$. The SF of Ref. [6] describes the nucleus as composed in $\sim$80% of nucleons occupying the shell-model states, with the remaining nucleons taking part in short-range interactions, typically forming quasi-deuteron pairs. The RFG model treats the nucleus as a fragment of noninteracting infinite nuclear matter of constant density, fixing the binding energy and the Fermi momentum—maximal nucleon momentum—to reproduce electron scattering data [8]. Taking the difference between the SF and RFG calculations as a rough estimate of the uncertainty of the SF results, I obtain that for energies above 1 GeV, nuclear effects introduce uncertainties not exceeding 0.27% for neutrinos and 0.46% for antineutrinos. While further comparisons are necessary for a reliable estimate of theoretical uncertainties, these results are reassuring for DUNE, which will collect most of the appearance events in this energy range.

However, at the kinematics relevant for T2K [9] and Hyper-Kamiokande (Hyper-K) [10], this is not the case. The cross sections' ratio significantly increases for low energies, as shown in Figs. 1(c) and 1(d). For example, at energy 0.6 GeV—corresponding to the peak of these experi-

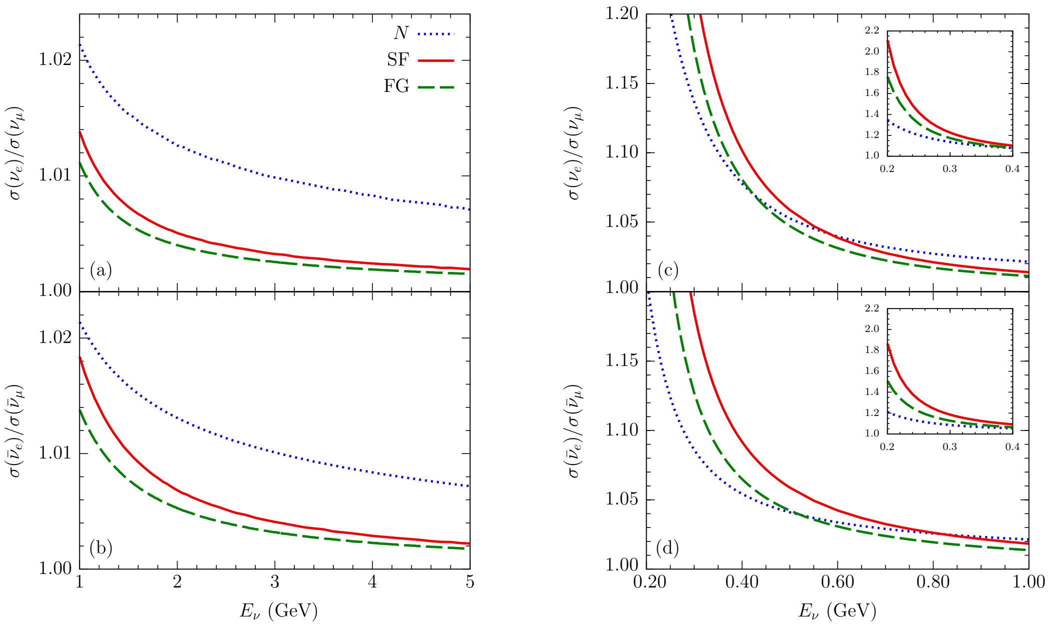

Figure 1: Ratio of the total cross sections $\sigma(\nu_e)/\sigma(\nu_\mu)$ [(a) and (c)] and $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$ [(b) and (d)] for charged-current quasielastic scattering off carbon calculated at high [(a) and (b)] and low [(c) and (d)] energies. The results for the relativistic Fermi gas model (dashed lines) and the spectral function approach (solid lines) are compared with the calculations for free nucleons (dotted lines).

ments' beam—the SF result is $3.86 \pm 0.74\%$ for neutrinos and $4.23 \pm 1.15\%$ for antineutrinos, with theoretical uncertainties estimated as previously. At 0.4 GeV, it amounts to $10.2 \pm 2.1\%$ for ν's and $9.2 \pm 2.7\%$ for $\bar{\nu}$'s. With theoretical uncertainty increasing rapidly for decreasing energy and events being collected for reconstructed energies down to ∼0.2 GeV [11], the problem of accurate estimation of $\sigma(\nu_e)/\sigma(\nu_\mu)$ and its uncertainty is of great importance for the oscillation analysis at the kinematics of Hyper-K and T2K.

Based on the behavior of the total cross sections, one could expect the double differential cross for muon neutrinos to be always lower than the one for electron neutrinos. However, performing analysis within the continuum random phase approximation (RPA) and the local Fermi gas model with the RPA corrections, Martini *et al.* [12] have recently observed that at the kinematics where the charged-lepton's mass plays an important role—such as low scattering angles and low neutrino energies—the CC QE cross section for ν_μ's is higher than that for ν_e's.

Comparing the CC QE ν_e and ν_μ cross sections obtained within the RFG model with and without Pauli blocking, I have found [13] that in the theoretical approaches in which the kinematics of nucleon knockout is strongly constrained—such as the RFG model with Pauli blocking—the CC QE cross section of ν_μ's can, in fact, be higher than that of ν_e's at small scattering angles. However, this effect does not appear when the phase space available to nucleons is broader, as this is the case in nuclear models accounting for the shell structure determined in experiments measuring proton knockout from the nucleus using electron beams. In such models, supported by experimental data, also the double differential cross section for ν_e's is always higher than that for ν_μ's. This findings should be relevant for accurate oscillation analysis in the next generation of neutrino experiments.

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