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Neutral current (anti)neutrino scattering: Relativistic mean field and superscaling predictions

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ABSTRACT

We evaluate the neutral current quasi-elastic neutrino cross section within two nuclear models: the SuSA model, based on the superscaling behavior of electron scattering data, and the RMF model, based on relativistic mean field theory. We also estimate the ratio $(\nu p \to \nu p)/(\nu N \to \nu N)$ and compare with the MiniBooNE experimental data, performing a fit of the parameters M_A and $g_A^{(s)}$ within the two models. Finally, we present our predictions for antineutrino scattering.

1. Introduction

The study of neutral current mediated quasi-elastic (NCQE) neutrino–nucleus scattering in the GeV region is a powerful tool for hadronic and nuclear studies. We note that although in the tradition of neutrino experiments the term ‘elastic’, either neutral-current elastic or charged-current elastic is used for neutrino scattering off free nucleons as well as on nucleons bound on nuclei, in this work we will refer to the latter case with the more precise denomination of quasi-elastic (QE). NCQE can be used, on one hand, to obtain information on the structure of the nucleon, in particular on its strange quark content, on the other it represents a probe of nuclear dynamics complementary to neutrino charged current quasi-elastic (CCQE) scattering and electron scattering. Several theoretical investigations have been devoted to the study of this reaction making use of different nuclear models [1–4,6,7,5,8,9].

The MiniBooNE experiment [10] has recently reported a high-statistics measurement of the NCQE cross section on mineral oil (CH_2) and of the ratio $(\nu p \to \nu p)/(\nu N \to \nu N)$ between single-proton and proton + neutron cross sections. In this Letter we compare these measurements with the predictions of two relativistic nuclear models, the Super-Scaling-Approximation (SuSA) and the relativistic mean field (RMF) models, which have been previously applied to the CCQE process [11,12]. A detailed description of the two models can be found in Refs. [11] and [13]. Here we just recall their main ingredients: the SuSA approach is based on the assumption that the superscaling function [14] extracted from quasi-elastic electron scattering data can be implemented in the neutrino–nucleus cross section, the only differences between the two processes being related to the elementary reaction and not to the nuclear response; the RMF model provides a microscopic description of the process, where final-state interactions (FSI) are taken into account by using the same relativistic scalar and vector energy-independent potentials considered to describe the initial bound states. Both models give an excellent representation of the experimental superscaling function [13], in contrast to the relativistic Fermi gas (RFG), which fails to reproduce the electron scattering data.

It has been shown in Ref. [12] that, when applied to CCQE reactions, the RMF and SuSA models give similar results, although some difference arises: both models underestimate the MiniBooNE data [15], but the RMF gives a smaller discrepancy. It has been suggested by various authors [16–19] that the gap between theory and data can be filled by meson-exchange currents, multinucleon emission or particular treatments of final-state interactions. If one sticks to a simple nuclear description, such as the RFG model, presently used in neutrino interaction generators, the experimental increase in the cross section can be obtained by introducing a nucleon axial mass $M_A = 1.35$ GeV, significantly larger than the

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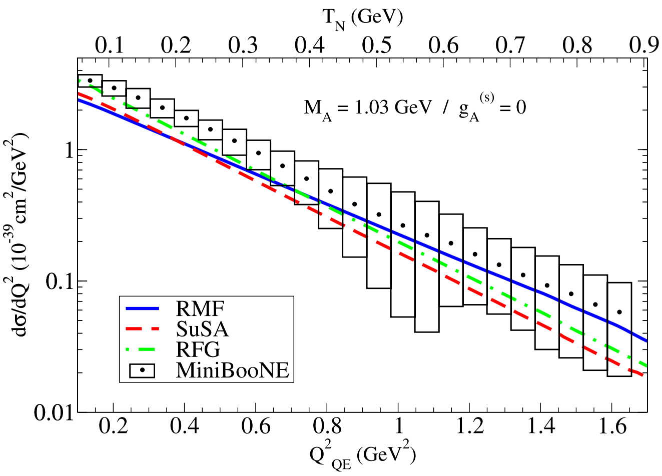

Fig. 1. NCQE flux-averaged cross section computed using the RMF (solid blue), SUSA (dashed red) and RFG (dot-dashed green) models and compared with the MiniBooNE data [10].

standard value $M_A = 1.03$ GeV [20], which simulates the additional nuclear effects not considered in the RFG.

2. Results and discussion

Let us now consider the neutral current (NC) process. In order to compare with MiniBooNE data on CH_2, we evaluate the following differential cross section per nucleon

$$\frac{d\sigma}{dQ^2} = \frac{1}{7} C_{\nu p,H}(Q^2)\frac{d\sigma_{\nu p\to\nu p,H}}{dQ^2} + \frac{3}{7} C_{\nu n,C}(Q^2)\frac{d\sigma_{\nu p\to\nu p,C}}{dQ^2} + \frac{3}{7} C_{\nu n,C}(Q^2)\frac{d\sigma_{\nu n\to\nu n,C}}{dQ^2}, \qquad (1)$$

which results from three contributions: scattering on free protons, bound protons in Carbon and bound neutrons in Carbon, each of them weighted by an efficiency correction function C_i and averaged over the experimental neutrino flux [10]. Results corresponding to the two models mentioned above as well as the RFG are shown in Fig. 1 as functions of the "quasi-elastic" four-momentum transfer Q_{QE} defined in [10] or of the outgoing nucleon kinetic energy T_N. The standard value $M_A = 1.03$ GeV has been taken for the axial mass, while the strange quark contribution to the axial form factor at $Q^2 = 0$, $g_A^{(s)}$ (or equivalently Δs), has been set to zero. For the electric and magnetic strangeness the results of a recent global analysis of PV electron–proton asymmetry data [21] ($\rho_s = 0.59$, $\mu_s = -0.02$) have been used. Note however that the cross section is essentially independent of ρ_s, μ_s [22].

We note that the SuSA cross section is smaller than the RFG one by about 20% and the two curves have essentially the same slope in Q^2. On the other hand the RMF result has a softer Q^2 behavior, with a smaller slope. This is at variance with the CCQE case, for which, as shown in Ref. [12], SuSA and RMF cross sections are very close to each other. This result indicates, as expected, that the NC data, for which the outgoing nucleon is detected, are more sensitive to the different treatment of final-state interactions than the MiniBooNE CC data, where the ejected nucleon is not observed.

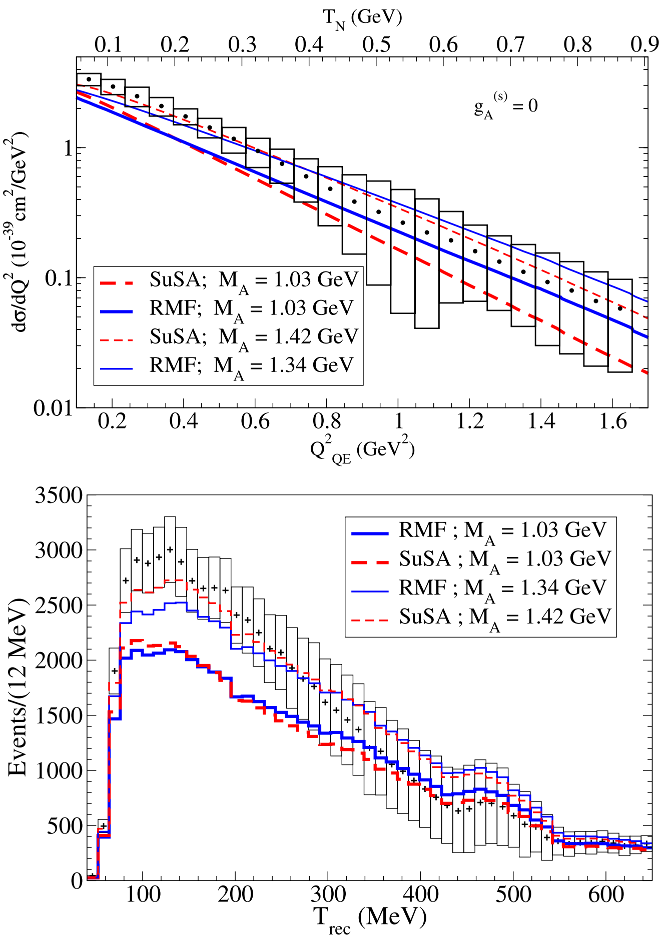

Fig. 2. NCQE flux-averaged cross section computed within the RMF (solid blue lines) and SuSA (dashed red lines) models, compared with MiniBooNE data [10] as a function of true energy on top panel and of the reconstructed energy on bottom panel, for different values of M_A (see text).

In Fig. 2 we illustrate the dependence of the cross section upon the axial mass M_A at strangeness $g_A^{(s)} = 0$. We compare results with the standard axial mass to the ones obtained with the value of M_A that provides the best fit to the cross section within either SuSA or RMF models. We fit the axial mass performing a χ^2 test using the true energy data from MiniBooNE [10] (top panel on Fig. 2) with the following χ^2 definition

$$\chi^2 = \sum_i \left(\frac{\mathrm{CS}_i^{\mathrm{exp}} - \mathrm{CS}_i^{\mathrm{theo}}}{\Delta \mathrm{CS}_i^{\mathrm{exp}}} \right)^2, \qquad (2)$$

where $\mathrm{CS}_i^{\mathrm{exp}}$ is the experimental cross section in the i-bin, $\mathrm{CS}_i^{\mathrm{theo}}$ is the predicted one and $\Delta\mathrm{CS}_i^{\mathrm{exp}}$ is the error in $\mathrm{CS}_i^{\mathrm{exp}}$. For $g_A^{(s)} = 0$, the 1-σ allowed regions of the axial mass for the two models are

$$M_A = 1.34 \pm 0.06 \text{ GeV} \quad \text{for RMF}, \qquad (3)$$

$$M_A = 1.42 \pm 0.06 \text{ GeV} \quad \text{for SuSA}, \qquad (4)$$

corresponding to $\chi^2/DOF = 16.5/22$ and $\chi^2/DOF = 4.7/22$, respectively. These have to be compared with $\chi^2/DOF = 46.2/22$ (RMF) and $\chi^2/DOF = 45.3/22$ (SuSA) for $M_A = 1.03$ GeV.

In Fig. 2 the RMF and SuSA results are compared with the MiniBooNE data as functions of the true (top panel) and reconstructed (bottom panel) energies. Whenever a physical quantity is measured there are distortions to the original distribution in the observed quantity. Experimentalists correct the data distribution using unfolding techniques. There is an alternative method, which is to report them in the reconstructed nucleon energy, without applying the unfolding procedure (and corresponding errors). To produce the reconstructed energy results we used the folding procedure detailed in Appendix B of Ref. [23]. We observe that both

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