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Meson-exchange currents and quasielastic predictions for neutrino-nucleus scattering

M.B. Barbaro*
Dipartimento di Fisica, Universita' di Torino and INFN, Torino, Italy
E-mail: barbaro@to.infn.it

J.E. Amaro
Departamento de Física Atómica, Molecular y Nuclear, and Instituto de Física Teórica y Computacional Carlos I, Universidad de Granada, Spain
E-mail: amaro@ugr.es

J.A. Caballero
Departamento de Física Atómica, Molecular y Nuclear, Universidad de Sevilla, Spain
E-mail: jac@us.es

A. De Pace
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Italy
E-mail: depace@to.infn.it

T.W. Donnelly
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
E-mail: donnelly@mit.edu

G.D. Megias
Departamento de Física Atómica, Molecular y Nuclear, Universidad de Sevilla, Spain
E-mail: megias@us.es

I. Ruiz Simo
Departamento de Física Atómica, Molecular y Nuclear, and Instituto de Física Teórica y Computacional Carlos I, Universidad de Granada, Spain
E-mail: ruizsig@ugr.es

We review some recent progress in the study of electroweak interactions in nuclei within the SuSAv2-MEC model. The model has the capability to predict (anti)neutrino scattering observables on different nuclei. The theoretical predictions are compared with the recent T2K $\nu_\mu - {}^{16}$O data and good agreement is found at all kinematics. The results are very similar to those obtained for $\nu_\mu - {}^{12}$C scattering, except at low energies, where some differences emerge. The role of meson-exchange currents in the two-particle two-hole channel is analyzed in some detail. In particular it is shown that the density dependence of these contributions is different from what is found for the quasielastic response.

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*Speaker.

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Nuclear physics plays a crucial role in the analysis of neutrino oscillation experiments: nuclear modeling uncertainties in the description of neutrino-nucleus scattering represent the main source of systematic error for long baseline neutrino experiments which aim at precision measurements of neutrino oscillation parameters.

In order to test and constrain nuclear models to be used in these analyses, it is necessary to use informations provided by other experiments, in particular electron-nucleus scattering data. This is the basis of the SuSA model [1], which exploits the scaling and superscaling properties exhibited by electron scattering data in order to predict neutrino-nucleus observables. In its more recent version, SuSAv2 [2], the model also takes into account the behavior of the responses provided by the Relativistic Mean Field (RMF): in particluar, the natural enhancement of the transverse electromagnetic response provided by RMF, a genuine dynamical relativistic effect, is incorporated in the SuSAv2 approach. However, while the RMF approach works properly at low to intermediate values of the momentum transfer q, where the effects linked to the treatment of the final-state interactions (FSI) are significant, it fails at higher q due to the strong energy-independent scalar and vector RMF potentials, whose effects should instead become less and less important with increasing momentum transfer. In this regime the relativistic plane-wave impulse approximation (RPWIA) is indeed more appropriate. Therefore, the SuSAv2 model incorporates both approaches, RMF and RPWIA, and combines them through a q-dependent "blending" function that allows a smooth transition from low/intermediate (validity of RMF) to high (RPWIA-based region) q-values.

The SuSAv2 predictions for inclusive (e,e') scattering on ^{12}C have been presented in [3], where they are shown to provide a remarkably good description of the data for very different kinematical situations. In order to perform such comparison the SuSAv2 model has been extended from the the quasielastic (QE) domain to the inelastic region by employing phenomenological fits to the single-nucleon inelastic electromagnetic structure functions. Furthermore, ingredients beyond the impulse approximation, namely two-particle-two-hole (2p2h) excitations, have been added to the model. These contributions, corresponding to the coupling of the probe to a pair of interacting nucleons and associated to two-body meson exchange currents (MEC), are known to play a very significant role in the "dip" region between the QE and Δ peaks. In the SuSAv2 approach they are treated within the Relativistic Fermi Gas (RFG) model, which allows for an exact and fully relativistic calculation, as required for the extended kinematics involved in neutrino reactions.

The increasing experimental interest in theoretical predictions for neutrino cross sections on targets other than ^{12}C, specifically ^{40}Ar and ^{16}O, requires the extension of the above calculation performed for carbon to different nuclei. In this context, the similarities and differences between charged current (anti)neutrino scattering with no pions in the final state (the so-called CC0π process) on ^{16}O and ^{12}C have been explored [4]. The CC0π process receives contributions from two different reaction mechanisms: QE scattering and excitation of 2p2h states. These two mechanisms in general have different dependences on the nuclear species, namely they scale differently with the nuclear density. This was shown in Ref. [5] and is illustrated in Fig. 1, where the transverse electromagnetic MEC response, $R^T_{\rm MEC}$, is plotted versus the energy transfer ω, together with the functions

$$\widetilde{F}^T_{\rm MEC} \equiv \frac{m_N^2}{k_F^2} \times \frac{R^T_{\rm MEC}(q,\omega)}{ZG^2_{Mp}(\tau)+NG^2_{Mn}(\tau)} \equiv \frac{m_N^2}{k_F^2} \times F^T_{\rm MEC}(q,\omega) \qquad (1)$$

and

$$f_{\text{MEC}}^T \equiv k_F \times \frac{R_{\text{MEC}}^T(q,\omega)}{ZG_{Mp}^2(\tau)+NG_{Mn}^2(\tau)} \equiv k_F \times F_{\text{MEC}}^T(q,\omega) \tag{2}$$

plotted versus the usual quasielastic scaling variable ψ'_{QE} [1] for three values of the momentum transfer q and for the symmetric nuclei ^{4}He, ^{12}C, ^{16}O and ^{40}Ca. In the above equations k_F is the Fermi momentum, $F_{\text{MEC}}^T(q,\omega)$ is the reduced MEC transverse response and $G_{Mp(n)}$ is the proton (neutron) magnetic form factor. The cases of ^{12}C and ^{16}O are clearly relevant for ongoing neutrino oscillation studies, whereas the case of ^{40}Ca is a symmetric nucleus lying close to the important case of ^{40}Ar. For comparison, ^{4}He is also displayed. The results show that the reduced 2p2h

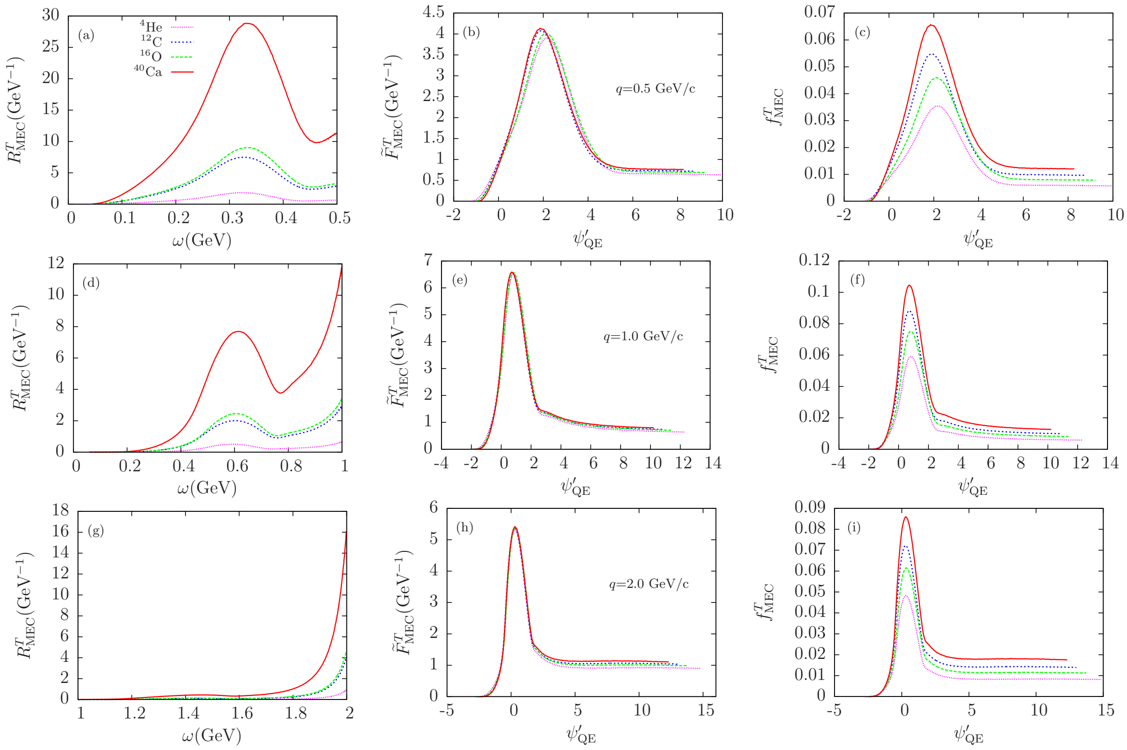

Figure 1: (Color online) The 2p2h MEC response (first column), the corresponding scaled response $\widetilde{F}_{\text{MEC}}^T$ defined by Eq. (1) (second column) and the superscaling function f_{MEC}^T defined by Eq. (2) (third column) for four nuclei and three values of momentum transfer q. Figure from Ref. [5].

response $F_{\text{MEC}}^T(q,\omega)$ roughly scales as k_F^2 when represented as a function of ψ'_{QE} (second column), *i.e.*, the scaled 2p2h MEC response shown there coalesces at the peak into a universal result. This scaling law is even more accurate at the peak of the 2p2h response when a scaling variable ψ'_{MEC}, specifically devised for this region, is used (see Ref. [5]). On the other hand the usual second-kind scaling observed in the QE regime, which would require that the function f_{MEC}^T be independent of k_F, is clearly violated (third column).

Before showing predictions for neutrino scattering on an oxygen target, we validate the model by comparing with electron scattering data, as shown in Fig. 2. In the case of ^{16}O the available (e,e') data cover only a limited kinematic region corresponding to six different sets of the electron incident energy E_i and scattering angle θ [6, 7]. In the calculation we have employed the Gari-Krumpelmann (GKex) model for the elastic electromagnetic form factors [8], whereas the inelastic structure functions are described making use of the Bosted and Christy parametrization [9, 10]. The contribution of the 2p2h MEC is also included in both the longitudinal and transverse channels, although the latter are largely dominant in the electromagnetic case. The value of the Fermi momentum is fixed to $k_F = 230$ MeV/c. In all the cases we present the separate contributions for the QE, 2p2h MEC and inelastic regimes. As observed, the SuSAv2-MEC predictions are in very good accordance with data for all kinematical situations. Although the relative role of the 2p2h-MEC effects is rather modest compared with the QE and inelastic contributions, its maximum is located in the dip region between the QE and inelastic peaks. This makes 2p2h-MEC essential in order to describe successfully the behavior of (e,e') data against the transferred energy ω: data in the dip region can only be reproduced by adding MEC effects to the tails of the QE and inelastic curves. Indeed, at the peak of the 2p2h response the three contributions are comparable in size.

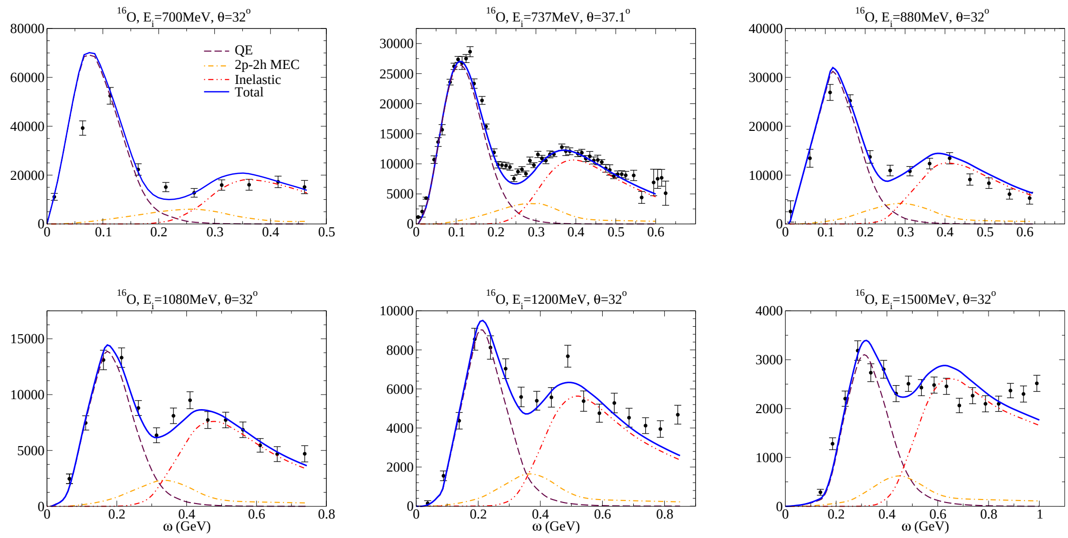

Figure 2: (Color online) Comparison of inclusive ^{16}O(e,e') cross sections and predictions of the SuSAv2-MEC model. The separate contributions of the pure QE response (dashed violet line), the 2p2h MEC (dot-dashed), inelastic (double-dot dashed) are displayed. The sum of the three contributions is represented with a solid blue line. The data are from [6] and [7]. Figure from Ref. [4].

Having successfully tested the model, we now show in Fig. 3 the results for CC neutrino reactions on ^{16}O. Each panel presents the double differential cross section averaged over the T2K muonic neutrino flux versus the muon momentum for fixed bins of the muon scattering angle. These kinematics correspond to the recent (ν_μ, μ) CC0π data collected by the T2K experiment [11]. Contrary to the (e,e') cross sections previously shown, here only the QE and 2p2h MEC contributions are taken into account, as this is consistent with the analysis of the data, that is restricted to charged-current processes with no pions in the final state . We show the separate contributions of the pure QE, the 2p2h MEC and the sum of both. Notice the role of the MEC effects compared with the pure QE ones — of the order of $\sim$15% at the maximum of the peak, except for forward angles, where they represent about 20% of the total cross section. Furthermore, the MEC peak compared with the QE one is shifted to smaller p_μ-values. These results, which are also observed in the case of T2K-^{12}C (see [12]), are somehow different from the ones found in the analysis of other experiments, namely, MiniBooNE and MINERvA, that show 2p2h MEC relative effects to be larger and the peak location more in accordance with the QE maximum. This is connected with the much narrower distribution presented by the T2K neutrino flux, that explains the smaller 2p2h MEC contribution and the location of its peak.

The SuSAv2-MEC approach provides predictions in good agreement with T2K data in most of the situations, although here 2p2h MEC effects do not seem to improve in a significant way the comparison with data. This is at variance with other experiments, MiniBooNE and MINERvA, and it is connected with the minor role played by MEC. Notice that in most of the situations, both the pure QE and the total QE+MEC predictions describe data with equal success. A similar discussion was already presented in [12] for ^{12}C.

The model predictions for antineutrino $\bar{\nu}_\mu$ scattering on water, for which data are not yet available, can be found in Ref. [4].

Finally, we illustrate the dependence of the C/O differences upon the neutrino energy by displaying in Fig. 4 the total integrated cross section per neutron with no neutrino flux included versus the neutrino energy. More detailed comparisons can be found in Ref. [4]. The results shown here indicate that nuclear effects between these nuclei in the total cross section, that is, including both the QE and 2p2h MEC contributions, are very tiny, at most of the order of $\sim$2-3%. This minor difference is also observed for the pure QE response (slightly higher for carbon) and the 2p2h MEC (larger for oxygen). This is connected with the differing scaling behavior shown by the QE and 2p2h MEC responses with the Fermi momentum, and the very close values of k_F selected for the two nuclei. Upon including both the QE and 2p2h MEC contributions, one observes that nuclear effects in the total cross section are very tiny. We also show the effect of making a "cut" at $\omega = 50$ MeV, namely, setting any contribution from below this point to zero. This has been used in past work as a crude sensitivity test to ascertain the relative importance of the near-threshold region. If significant differences are observed when making the cut, then one should have some doubts about the ability of the present modeling (indeed, likely of all existing modeling) to successfully represent the cross section in this region. What we observe for the total cross section shown in Fig. 4 are relatively modest effects from near-threshold contributions, although one should be aware that this is not so for differential cross sections at very forward angles where small-ω contributions can be relatively important (see [4]).

Summarizing, the SuSAv2 model, based on superscaling and complemented with the addition of 2p2h contributions induced by meson exchange currents, has been applied to the simultaneous study of electron and CC neutrino scattering for two different nuclei, carbon and oxygen. Good agreement is found with all existing data. The scaling properties of the 2p2h response versus the nuclear density have also been analyzed and a scaling law, different from the one obeyed by the QE response, has been defined. This can be useful to estimate the importance of these contributions in different nuclei and extrapolate results from one nucleus to another without performing the explicit calculation. Given the success of the comparison of the model predictions with both inclusive (e,e') and CCν data, we have increased confidence in employing the approach for heavier nuclei. New features are likely to emerge in these cases and we shall explore their consequences in forthcoming work.

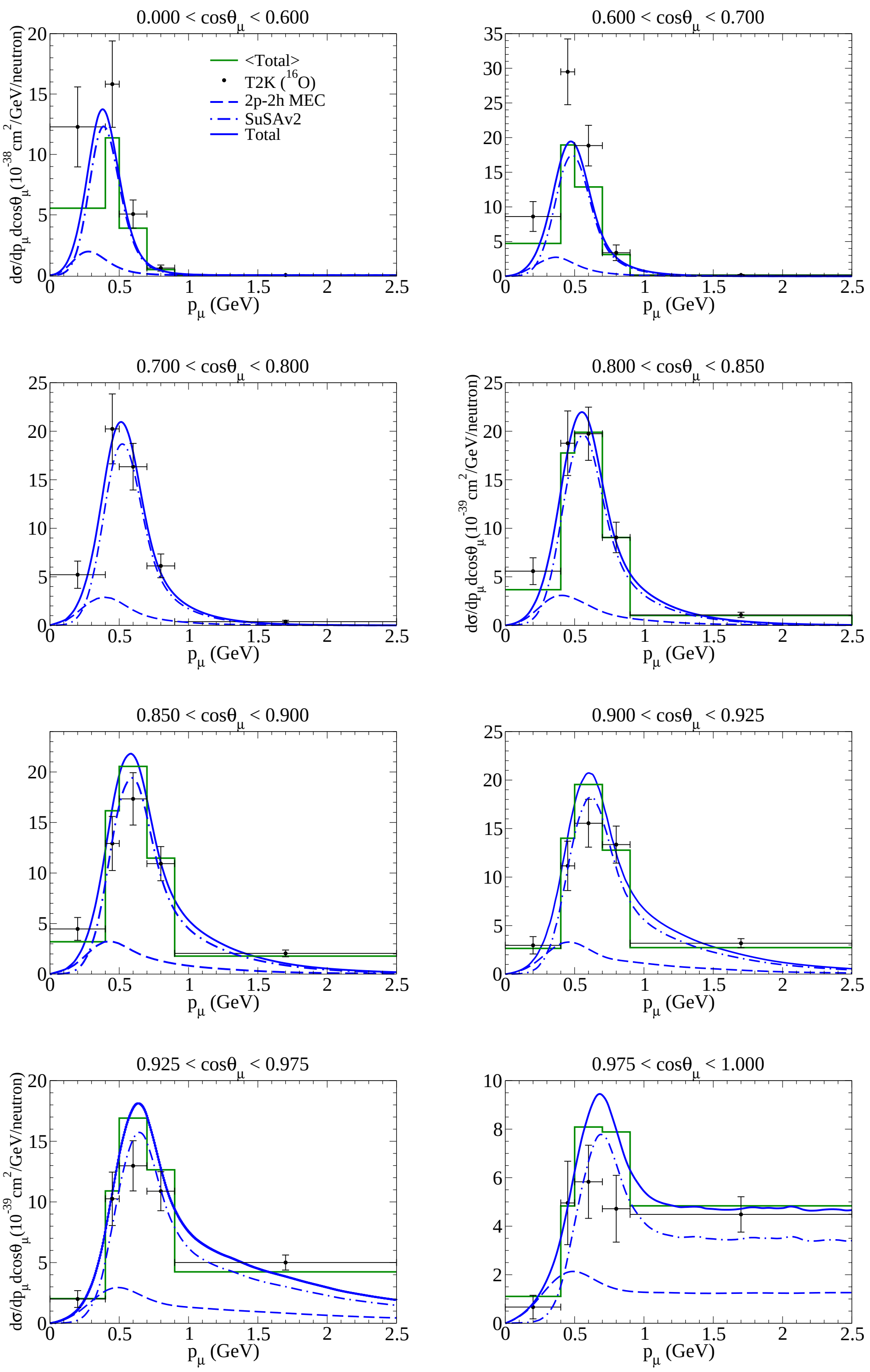

Figure 3: (Color online) T2K flux-folded double differential cross section per target neutron for the ν_μ CCQE process on ^{16}O displayed versus the muon momentum p_μ for various bins of $\cos\theta_\mu$ obtained within the SuSAv2-MEC approach. QE and 2p2h MEC results are shown separately. The histogram represents the theoretical average of the total result over each bin of p_μ. The data are from [11]. Figure from Ref. [4].

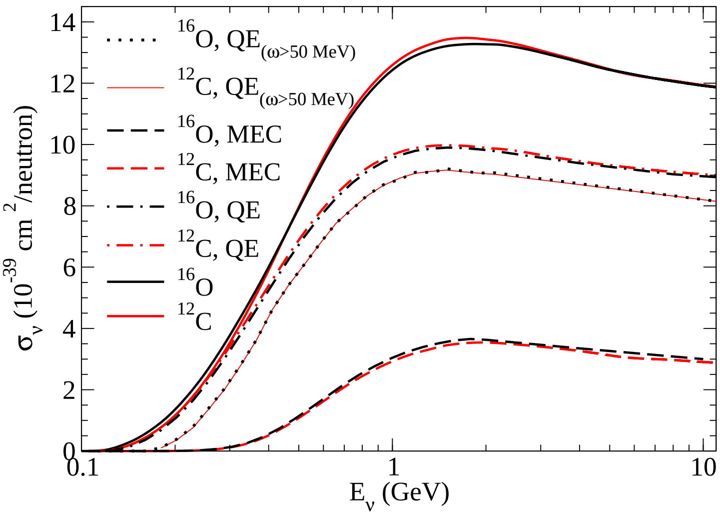

Figure 4: (Color online) Total ν_μ cross section per nucleon as a function of the neutrino energy evaluated for ^{12}C and ^{16}O nuclei. Separate contributions of the pure QE (dot-dashed) and 2p2h MEC (dashed). The effect of making a cut in ω below 50 MeV for the QE contribution is also shown. Figure from Ref. [4].

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