

Confronting electron- and neutrino-nucleus scattering

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Abstract. The analysis of the sample of charged current quasi elastic events collected by the MiniBooNE Collaboration suggests that the scheme successfully employed to describe electron-nucleus scattering fails to explain neutrino-nucleus cross sections. I argue that, due to flux average, the double differential neutrino-nucleus cross section does not allow for a clearcut determination of the dominant reaction mechanism. A systematic study of the large body of electron scattering data may help to identify the processes, other than single nucleon knockout, contributing to the observed neutrino cross section.

Electron-nucleus scattering cross sections are usually analyzed at fixed beam energy, E_e , and electron scattering angle, θ_e , as a function of the electron energy loss ω . As an example, Fig. 1 shows the typical behavior of the inclusive cross sections at beam energy around 1 GeV. It is apparent that the different reaction mechanisms, yielding the dominant contributions to the cross section at different values of ω (corresponding to different values of the Bjorken scaling variable $x = Q^2/2m\omega$, where m is the nucleon mass and $Q^2 = 4E_e(E_e - \omega) \sin^2 \theta_e/2$) can be easily identified.

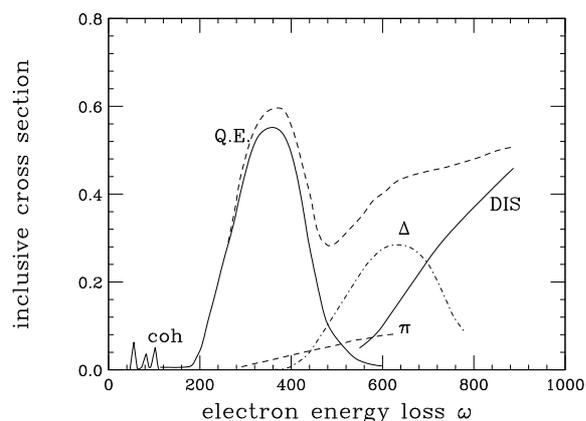


Figure 1. Typical behavior of the inclusive electron-nucleus scattering cross section at beam energy around 1 GeV, as a function of the electron energy loss ω .

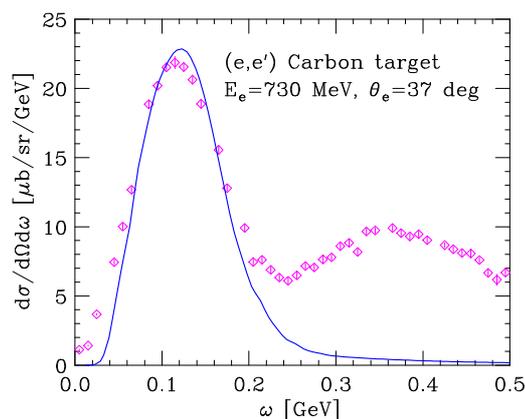


Figure 2. Quasi elastic electron-carbon cross section at beam energy $E_e = 730$ MeV and electron scattering angle $\theta_e = 37$ deg, plotted as a function of the energy loss ω [2]. The data points are from [3].

The bump centered at $\omega \sim Q^2/2m$, or $x \sim 1$, the position and width of which are determined by the momentum and removal energy distribution of the struck particle, corresponds to single nucleon knockout, while the structure visible at larger ω , or lower x , reflects the onset of coupling to two-nucleon currents, arising from meson exchange processes, excitation of nucleon resonances and deep inelastic scattering.

The quasi elastic electron-nucleus cross section can be described at quantitative level within the Impulse Approximation (IA), applicable when the magnitude of the three-momentum transfer, $|\mathbf{q}|$, is small compared to the average distance between nucleons in the target nucleus [1]. As an example, Fig. 2 shows the inclusive electron-carbon cross section at beam energy $E_e = 730$ MeV and electron scattering angle $\theta_e = 37$ deg, plotted as a function of the energy loss ω [2]. The data points are taken from [3], while the theoretical results have been obtained within the approach described in [1, 4], using a state-of-the-art parametrization of the vector nucleon form factors, extracted from the measured electron-proton electron-deuteron cross sections (for a review, see, e.g., [5]).

Applying the same scheme employed to obtain the solid line of Fig. 2 to neutrino scattering one gets the results shown in Fig. 3. The data points represent the double differential CCQE cross section of [6] averaged over the MiniBooNE neutrino flux, the mean energy of which is $\langle E_\nu \rangle = 788$ MeV, plotted as a function of the kinetic energy of the outgoing muon at different values of the muon scattering angle. The solid lines show the results of calculations performed using the same nuclear spectral functions and vector form factors employed in the calculation of the electron scattering cross section of Fig. 2 and the dipole parametrization of the axial form factor, with the axial mass $M_A = 1.03$ MeV [2] obtained from the world average of low statistics deuterium data [7, 8, 9].

Comparison between Figs. 2 and 3 indicates that the electron and neutrino cross sections corresponding to the same target and *seemingly* comparable kinematical conditions (the position of the QE peak in Fig. 2 corresponds to kinetic energy of the scattered electron ~ 610 MeV) cannot be explained using the same theoretical approach and the value of the axial mass resulting from deuterium measurements.

The authors of [6, 10, 11] suggested that the measured CCQE cross sections may be explained by advocating a larger value of M_A , that should be regarded as an *effective* axial mass, modified by nuclear effects not included in the Fermi gas model employed in data analysis. However, most theoretical models of the CCQE cross section (for recent reviews see [12]) fail to support this explanation. In addition, the analysis of the large body of electron scattering data provide overwhelming evidence that the vector form factors are *not* modified in the nuclear medium.

In [2, 13] it is argued that the interpretation of the data sample of [6] as CCQE events may be hampered by the fact that, as the energy of the incoming beam is not fixed, the observed energy of the outgoing charged lepton *does not* uniquely determine the energy transfer to the target.

The implications of flux average can be easily understood considering the neutrino cross section at muon energy corresponding to the maximum of the spectrum shown in the upper panel of Fig. 3, i.e. $T_\mu = 0.55$ GeV and $\cos\theta = 0.75$. In this kinematics, $x = 1$ and 0.5 correspond to neutrino energy $E_\nu = 0.788$ and 0.975 GeV, respectively. As the values of the MiniBooNE flux corresponding to these energies are within less than 20% of one another, flux integration leads to collect contributions from different regimes, i.e. different reaction mechanisms, with about the same probability.

This feature can be best illustrated using the measured electron-carbon scattering cross sections. Figure 4 shows the data from [3, 14], taken at electron scattering angle $\theta_e = 37$ deg and beam energies ranging between 0.730 and 1.501 GeV, plotted as a function of the energy of the outgoing electron. It clearly appears that the energy bin corresponding to the top of the quasi elastic peak at $E_e = 0.730$ GeV, shown by the shaded area, receives significant contributions

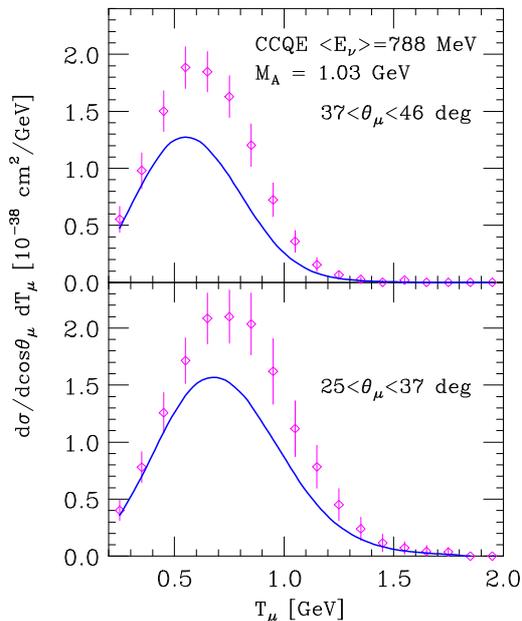


Figure 3. Flux averaged double differential CCQE cross section measured by the Mini-BooNE collaboration [6], shown as a function of the kinetic energy of the outgoing muon. The upper and lower panels correspond to different values of the muon scattering angle. The theoretical results have been obtained in [2], using the formalism described in [1, 4], the same vector form factors employed in the calculation of the electron scattering cross section of Fig. 2, and a dipole parametrization of the axial form factor with $M_A = 1.03 \text{ MeV}$.

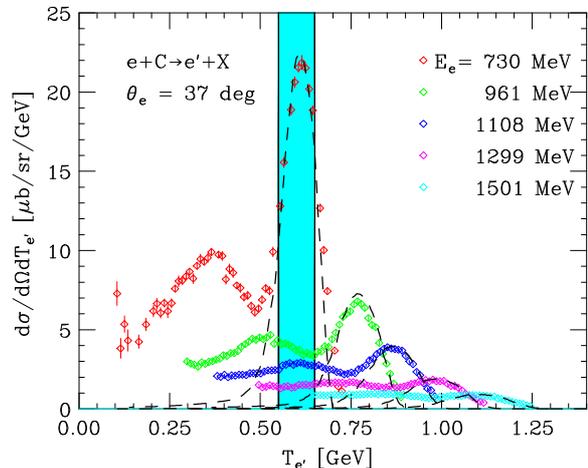


Figure 4. Inclusive electron-carbon cross sections at $\theta_e = 37 \text{ deg}$ and beam energies ranging between 0.730 and 1.501 GeV [3, 14]. The dashed lines represent the single nucleon knock out contribution, computed within the approach described in [1, 4]. The shaded area shows the energy bin corresponding to the peak of the cross section of Fig. 2.

from cross sections corresponding to different beam energies and different values of x .

The data displayed in Fig. 4 strongly suggest that the description of the flux-integrated CCQE neutrino nucleus cross section requires the inclusion of reaction mechanisms other than single nucleon knockout. According to the authors of [15, 16], the most important competing mechanism is multinucleon knockout, leading to two particle-two hole (2p2h) final states. Note that in neutrino experiments this final states cannot be distinguished from the one particle-one hole final states associated with single nucleon knockout.

Multinucleon knockout is known to occur due to i) initial state nucleon-nucleon correlations, ii) final state interactions between the struck nucleon and the spectator particles and iii) coupling to the two-body nuclear electroweak current.

Correlations between nucleons in the target ground state give rise to the tail extending to large ω , clearly visible in Fig. 2. However, their contribution, strongly constrained by semi-inclusive $(e, e'p)$ data [17] turns out to be quite small (less than 10% of the integrated spectrum). In principle, this reaction mechanism might be clearly identified detecting two nucleons moving in opposite directions with momenta much larger than the Fermi momentum ($\sim 250 \text{ MeV}$).

Final state interactions are not expected to play a relevant role in this context, as their main effects, which amounts to a shift and a redistribution of the inclusive strength, mostly

affects the region of low energy loss, corresponding to $x > 1$.

The most important correction is likely to arise from processes involving the nuclear two-body current, as advocated by the authors of [15, 16]. It is long known that inclusion of these processes is needed to explain the nuclear electromagnetic response in the transverse channel [18]. In addition, their contribution turns out to decrease as the momentum transfer increases. This behavior may explain why the CCQE data at high neutrino energies collected by the NOMAD collaboration [9] can be described without any modification of the value of the nucleon axial mass.

In conclusion, comparison between electron and neutrino scattering data suggest that the analysis of the flux-averaged neutrino cross sections requires the development of models including a variety of relevant reaction mechanisms. While the approaches developed in [15, 16] certainly represent an important step towards the achievement of this goal, more theoretical work is still needed, e.g. to extend the applicability of the models to the regions of pion production and deep inelastic scattering.

The critical requirement to be met in developing new theoretical approaches will be consistency, i.e. the ability to describe different kinematical regimes using the same dynamical model. Within *ab initio* nuclear many-body theory this amounts to requiring that the target initial and final states be obtained from the same hamiltonian, fitted to the properties of exactly solvable few-nucleon systems, which also largely determines the structure of the vector two-body current through the continuity equation.

Acknowledgments

The results discussed in this paper have been obtained in collaboration with Pietro Coletti and Davide Meloni. An illuminating discussion with Georgia Karagiorgi and Camillo Mariani is also gratefully acknowledged. Finally, I would like to express to the organizers of NUFACT11 my deepest appreciation for setting up a most enjoyable and fruitful meeting.

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