Lepton-nucleus scattering and effects of MEC: CCQE-like neutrino cross sections at energies of the NOvA experiment

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Abstract

- The scattering of leptons on carbon and calcium targets are analyzed using an approach that incorporates the contributions to the nuclear response functions from the quasi-elastic (QE), inelastic process (RES), and two-particle and two-hole meson exchange current (2p-2h MEC). This RDWIA+MEC+RES approach is successfully tested against $^{12}C(e,e')$ and $^{40}Ca(e,e')$ scattering data. A fit of the RDWIA+MEC approach to the MiniBooNE neutrino data is performed and the best fit value of nucleon axial mass M_A = 1.2 GeV is obtained. The flux-integrated CCQE-like differential cross sections for neutrino scattering at energies of the NOvA experiment are estimated.

Introduction

- The modeling of neutrino-nucleus interactions in the energy range 0.2-5 GeV is one of the most complicated issues facing neutrino oscillation experiment. Weak interactions of neutrino probe the nucleus in a similar way as electromagnetic electron interactions. The vector part of the electroweak interaction can be inferred directly from electron scattering and influence of nuclear medium is the same as in neutrino-nucleus scattering. Precise electron scattering data give opportunity to validate nuclear model employed in neutrino physics.

Model

- We calculated the double-differential $^{12}C(e,e')$ and $^{40}Ca(e,e')$ cross sections within the RDWIA+MEC+RES approach [1-3]. In this model the electromagnetic response functions can be written as sum of the QE, MEC, and inelastic response functions. We describe QE electron-nuclear scattering using the relativistic distorted-wave impulse approximation (RDWIA) approach. The short range nucleon-nucleon correlations in nuclei and FSI effects are taking into account. The electromagnetic MEC response functions we evaluate using accurate parametrizations of the exact MEC calculations. The inelastic response functions were calculat using the parametrization for the neutron and proton structure functions. This approach is based on an empirical fit to describe the measurements of inelastic electron-proton and electron-deuteron cross sections.

Result

The double-differential $d^2\sigma/d\omega d\Omega$ cross sections calculated in the RDWIA+MEC+RES model for electron scattering on carbon and calcium [1] as functions of the energy transfer ω are shown in **Fig.1** and **Fig.2**, respectively, and compared with data from Ref. [4]. Each panel corresponds to the fixed value of the incident electron energy E and scattering angle θ. As shown in the key, the separate QE, 2p-2h MEC, and inelastic contributions are presented. The systematic analysis shows that this model leads to a good description of the whole set of (e,e') data, validating the reliability of our prediction.

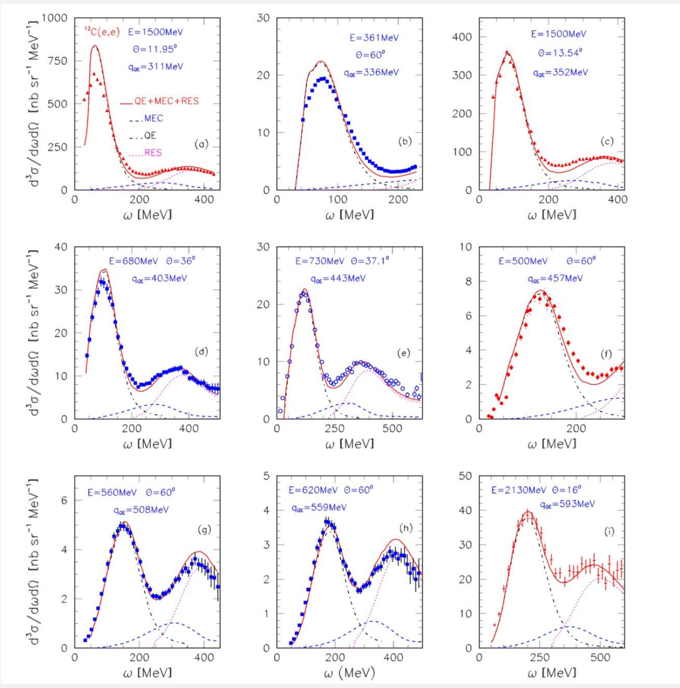

Fig.1: The $^{12}C(e,e')$ double-differential cross sections as functions of energy transfer ω compared with the RDWIA+MEC+RES prediction.

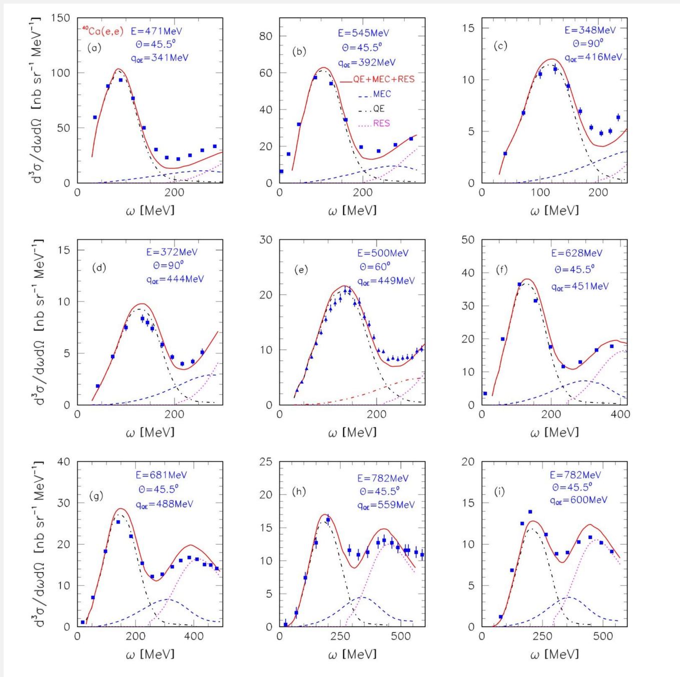

Fig.2: Same as **Fig.1** but for the calcium target.

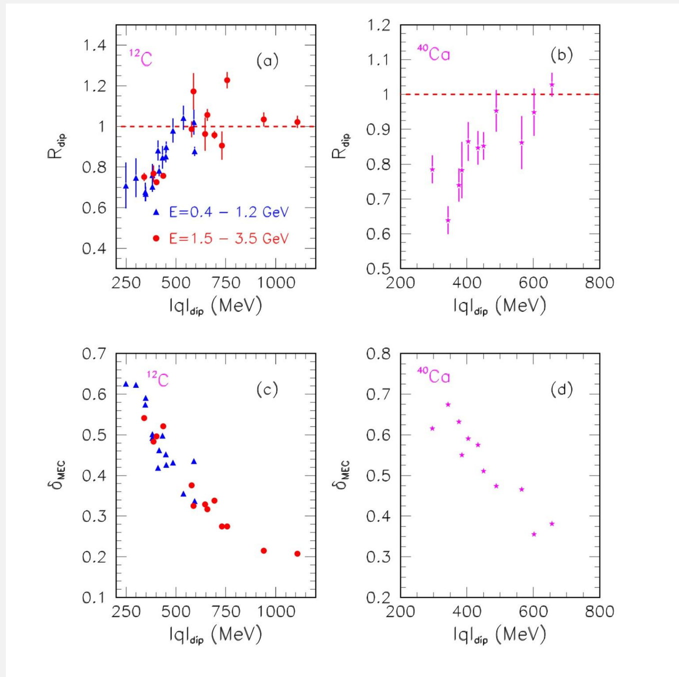

Fig.3: Ratio R^C_{dip} for carbon **(a)** and R^{Ca}_{dip} for calcium **(b)** as a function of $|q|_{dip}$. The ratios R^C_{dip} are shown for the two ranges of the incident electron energy E = 0.4 − 1.2 GeV (filled triangles) and E = 1.5 − 3.5 GeV (filled circles). The results for ratios δ_{MEC} vs $|q|_{dip}$ for electron scattering on ^{12}C **(c)** and ^{40}Ca **(d)**.

We calculated $R_{dip}=(d^2\sigma/d\omega d\Omega)_{cal}/(d^2\sigma/d\omega d\Omega)_{data}$ ratios at the momentum transfer $|q|_{dip}$ that corresponds to the minimum of the measured cross section in the dip region between quasielastic and Δ peaks. Here $(d^2\sigma/d\omega/d\Omega)_{cal}$ and $(d^2\sigma/d\omega/d\Omega)_{data}$ are calculated and measured cross sections, correspondingly. We calculated $\delta_{MEC} = (d^2\sigma/d\omega d\Omega)_{MEC} / (d^2\sigma/d\omega d\Omega)$ ratios vs $|q|_{dip}$, where the $(d^2\sigma/d\omega d\Omega)_{MEC}$ is the 2p-2h MEC differential cross sections. The R_{dip} increases with $|q|_{dip}$ from 0.7 to 1 at $|q|_{dip}$ =500 MeV and does not depend on electron energy. The contribution δ_{MEC} reduces with $|q|_{dip}$ from 0.65 to 0.42 at $|q|_{dip}$ =500 MeV.

The MiniBooNE neutrino data set [5], obtained in a kinematical range, that significantly overlaps with the range available to the NOvA experiment, is used in the CCQE-like fit (QE+MEC). These data have been released as flux-integrated double-differential cross sections $d^2\sigma/d\cos\theta dT$ (T and θ are muon kinetic energy and scattering angle, correspondingly), and as differential cross section $d\sigma/dQ^2$. The fit of the RDWIA+MEC model to the neutrino MiniBooNE data was made in Ref.[3] and the best fit value of M_A=1.2 GeV was obtained. In **Figs.4** and **5** the differential cross sections per neutron calculated with this value of M_A are presented. The MiniBooNE data are shown as point.

We show the separate contributions from QE and 2p-2h MEC. The results for $d^2\sigma/d\cos\theta dT$ cross sections against energy T averaged over $\cos\theta$ bins are show in **Fig.4**. In **Fig.5** the results averaged over the energy bins as functions of the $\cos\theta$ are presented. These graphs shows that the 2p-2h MEC contributions are essential and the RDWIA+MEC model is able to reproduce the data.

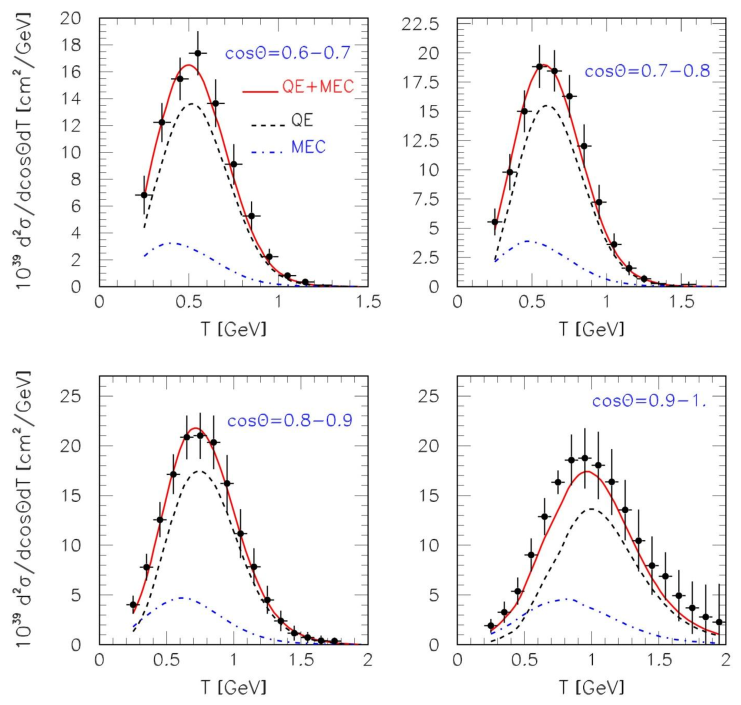

Fig.4: $d^2\sigma/d\cos\theta dT$ cross section per neutron vs T for four muon scattering angle bins: $\cos\theta$=(0.6-0.7), (0.6-0.8), (0.8-0.9) and (0.9-1).

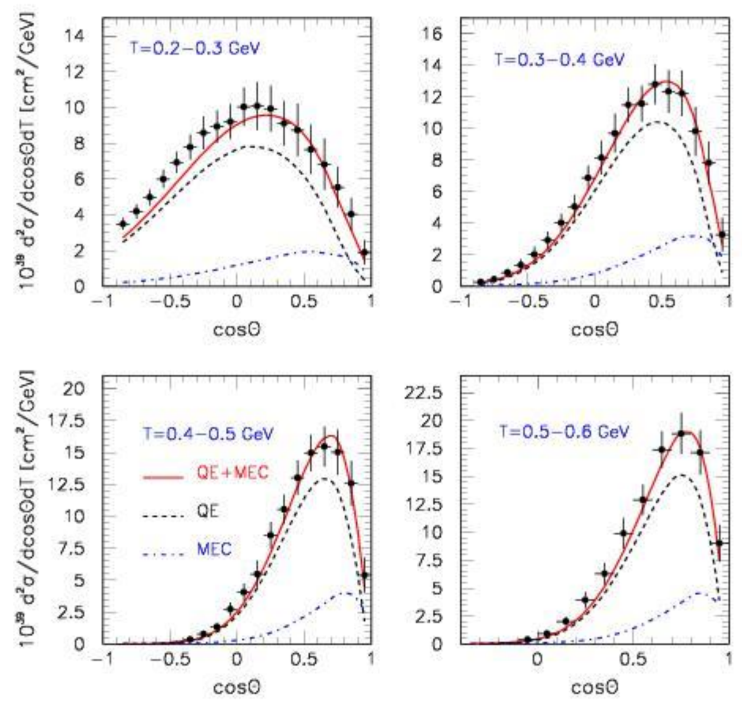

Fig.5: $d^2\sigma/d\cos\theta dT$ cross section per neutron vs $\cos\theta$ for four muon energy bins: T(GeV)=(0.2-0.3), (0.3-0.4), (0.4-0.5) and (0.5-0.6).

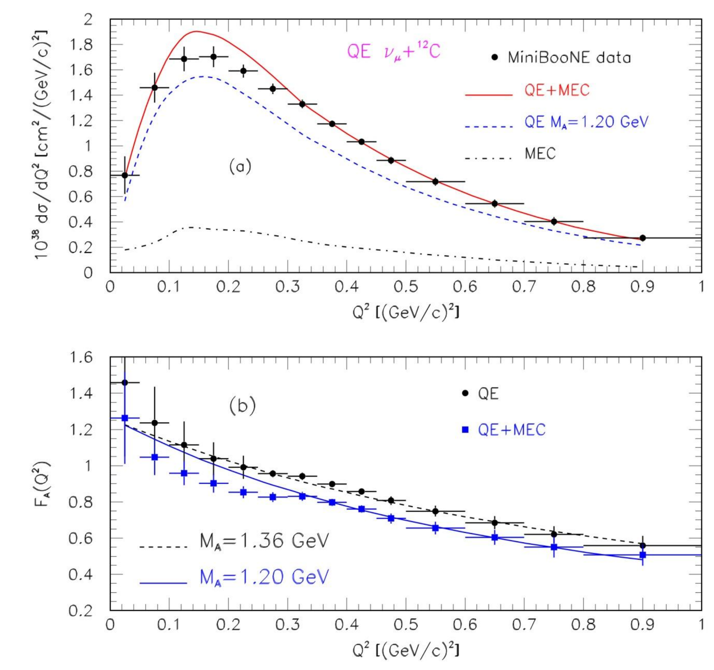

Fig.6: Flux-integrated $d\sigma/dQ^2$ cross section (upper panel) and $F_A(Q^2)$ extracted from the MiniBooNE data (lower panel) vs Q^2. Upper panel: Calculation from the RDWIA+MEC with M_A=1.2 GeV. Lower panel: The axial form factor extracted within the RDWIA+MEC (RDWIA), and the result of the dipole parametrization with M_A=1.2(1.36) GeV.

The best-fit of the $d\sigma/dQ^2$ distribution is compared with data in **Fig.6(a)**. To extract the values of the axial form factor the measured $d\sigma/dQ^2$ distribution was used [3]. The result $F_A(Q^2)$ as a function of Q^2 is shown in **Fig.6(b)**. Also shown in this figure is the result obtained without the MEC contribution. The values of the form factor, extracted in the RDWIA approach agree well with dipole parametrization with M_A=1.36 GeV.

Within the RDWIA+MEC approach with M_A=1.2 GeV we estimated the neutrino CCQE-like flux-integrated differential cross section $d^2\sigma/d\cos\theta dT$ at energies available at the NOvA experiments [6]. In **Figs.7** and **8** the cross sections per neutron predicted for the NOvA experiment are presented. The double-differential cross sections vs $\cos\theta$, averaged over energy bins are shown in **Fig.7**. In **Fig.8** the graphs are plotted against the kinetic energy T, and each panel corresponds to a bin in $\cos\theta$. In these figures, we show the separate contributions of the genuine QE and 2p − 2h MEC processes. We suggest that the uncertainties in these cross sections are of order of 12%.

The ratio of the CCQE-like $(d\sigma/dQ^2)_{QE+MEC}$ distribution to the genuine QE $(d\sigma/dQ^2)_{QE}$, $R_{MEC} = (d\sigma/dQ^2)_{QE+MEC} / (d\sigma/dQ^2)_{QE}$ calculated for the MiniBooNE and NOvA experiments is shown in **Fig.9**. As observed, in the NOvA case, the contribution of the 2p-2h MEC is about 8% higher than in the MiniBooNE experiment.

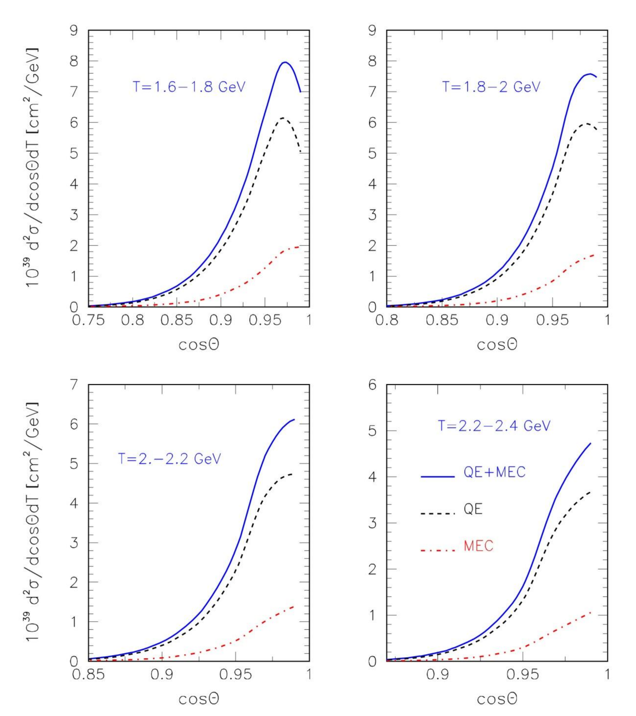

Fig.7

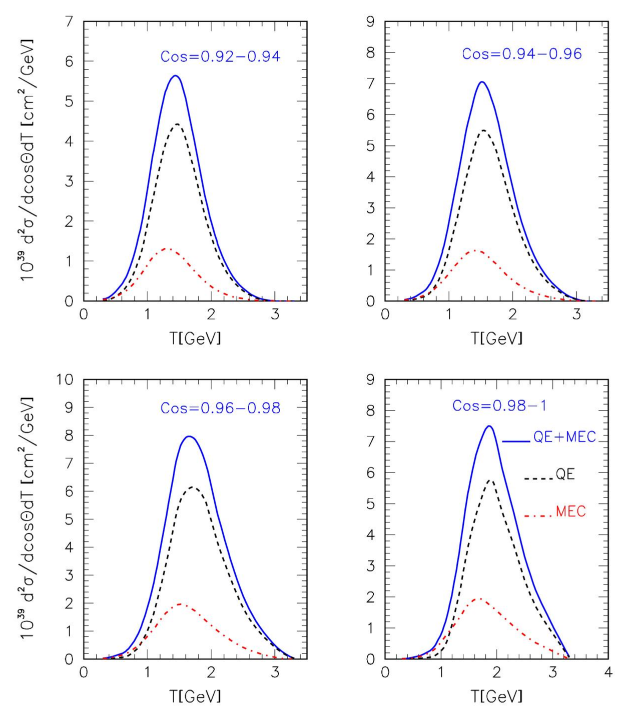

Fig.8

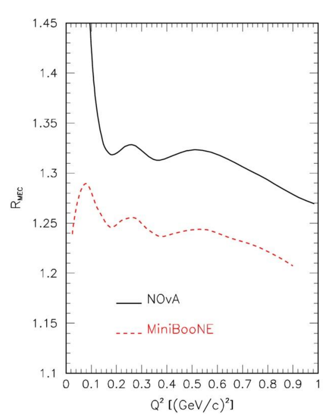

Fig.9: The ratio R_{MEC} as a function of Q^2 for the NOvA and MiniBooNE flux-integrated $d\sigma/dQ^2$ cross sections.

Conclusion

The RDWIA+MEC+RES approach with M_A=1.2 GeV is able to reproduce well the wide set of (e,e') data and the MiniBooNE measured cross sections. The flux-integrated CCQE-like differential cross sections for neutrino energies of the NOvA experiment were estimated.

References

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