Quasi-elastic Neutrino Scattering – an Overview

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Abstract. A non-technical overview of charge current quasi-elastic neutrino interaction is presented. Many body computations of multinucleon ejection which is proposed to explain recent large axial mass measurements are discussed. A few comments on recent experimental results reported at NuInt11 workshop are included.

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INTRODUCTION

Charge current quasi-elastic (CCQE) scattering is the most abundant neutrino interaction in experiments like MiniBooNE (MB) or T2K with a flux spectrum peaked below 1 GeV. Its full understanding is crucial for detail neutrino oscillation measurements.

The very definition of what does the term CCQE mean requires clarifications. In the case of neutrino-free nucleon scattering the reaction is:

\[ \nu + n \rightarrow l^- + p \quad \text{or} \quad \bar{\nu} + p \rightarrow l^+ + n \]  

(1)

with \( \nu, \bar{\nu}, l^\pm, p \) and \( n \) standing for: neutrino, antineutrino, charged lepton, proton and neutron respectively. In the case of neutrino-nuclear target reaction one would like to use the same definition and for that one needs a picture of a nucleus as composed from quasi-free nucleons (Impulse Approximation - IA [1]), like in the Fermi Gas (FG) model. In the \( \sim 1 \) GeV energy region typical values of momentum transfer are large enough and IA can be used as a reliable approximation. However, in inclusive neutrino measurements there is always a significant fraction of low momentum transfer apparently CCQE events and one cannot be sure that they are described in the proper way. A remedy is to impose suitable cuts in momentum transfer or in \( Q^2 \), or to use more sophisticated theoretical models [1].

1 From electron scattering experiments it is known that for momentum transfer \( q \leq 350 - 400 \) MeV/c IA based models fail to reproduce the data. In this region collective nuclear excitations become important and computational techniques like CRPA or RPA should be used [2]. Since \( q > \omega \) (\( \omega \) is the energy transfer) and \( Q^2 \equiv q^2 - \omega^2 > 0 \), the region of the failure of IA is contained in the domain \( Q^2 < 0.1 \) GeV\(^2\). In the case of neutrino CCQE interactions evaluated in the IA scheme a region \( q \leq 350 - 400 \) MeV/c corresponds to 15% – 20% of the total CCQE cross-section, independently on the neutrino energy \( E_\nu \) (for \( E_\nu < 500 \) MeV the fraction is even larger) [3]. Experimental groups invented various ad hoc ideas to deal with the low \( Q^2 \) problem. Eg. the MB collaboration introduced a parameter \( \kappa \) [4] to increase the Pauli blocking effect.
Nuclear environment affects CCQE interaction in other ways as well. There is a problem of Final State Interactions (FSI): hadrons arising in a primary interaction must propagate through nucleus before they can be detected. Thus, for an experimentalist it is natural to speak about QE-like events specified by a condition that there are no mesons in the final state. There is an important difference between QE and QE-like events because the latter include those in which a pion produced in the initial interaction was later absorbed inside the nucleus. There is also a possibility that for the CCQE primary interaction nucleon rescatterings result in pions in the final state.

### QUASIELASTIC AXIAL MASS

A theoretical description of free nucleon target CCQE reaction is based on the conserved vector current (CVC) and the partially conserved axial current (PCAC) hypotheses. As a result of a simple analysis the only one unknown quantity is the axial form-factor $G_A(Q^2)$ for which one typically assumes the dipole form $F_A(0)(1 + \frac{Q^2}{M_A^2})^{-2}$ with one free parameter, called the axial mass $M_A$. If deviations from the dipole form of $G_A$ are of a similar size as those in the case of electromagnetic form-factors it would be difficult to detect them and the basic assumptions described above seem to be well justified. Thus, the aim of CCQE experiments is to measure the value of $M_A$, the parameter describing free nucleon weak transition matrix element.

Measurements of $M_A$ typically focus on the shape of differential cross-section in $Q^2$ which is sensitive enough for quite precise evaluations of $M_A$. Investigations of only the shape of the $Q^2$ distributions of events do not rely on the (very limited) knowledge of the neutrino flux. The dependence of the total cross-section on $M_A$ can also be used as a tool to fix its value. The limiting value of the CCQE cross-section $\sigma_{CCQE}^{\infty}$ as $E_\nu \to \infty$ can be calculated in the analytical way assuming dipole vector and axial form-factors. In the exact formula the dependence of $\sigma_{CCQE}^{\infty}$ on $M_A$ is strictly speaking quadratic but in the physically relevant region it is with a good approximation linear. If a value of $M_A$ is increased from 1.03 to 1.33 GeV for $E_\nu > 1$ GeV the cross-section and (neglecting an impact of detector efficiency modifications) the expected number of CCQE events is raised by $\sim 30\%$ (for $E_\nu < 1$ GeV the increase is smaller).

In the past several measurements of $M_A$ were done on the deuterium target for which serious nuclear physics complications are absent. Until a few years ago it seemed that the results converge to a value of the order of 1.03 GeV. There is an additional argument in favor of a similar value of $M_A$ coming from the weak pion-production at low $Q^2$. PCAC based evaluation gives the axial mass value of $1.077 \pm 0.039$ GeV. On the contrary, all (with an exception of the NOMAD experiment) more recent high statistics measurements of $M_A$ are consistent with values of $1.03 \pm 0.03$ GeV.

In the early years of neutrino experiments many groups reported also fits to the non-dipole axial FF as motivated by quark model vector-dominance: $F_A(Q^2) = \frac{F_A(0)}{1 + \frac{Q^2}{M_A^2}} \exp \left( \frac{-Q^2(G_A^V)^2}{1 + \frac{Q^2}{4M_A^2}} \right)$\footnote{The quality of best fit values for $M_A$ in both models was similar. ANL and BNL collaborations considered also monopole and tripole axial FFs but the obtained fits were worse then the dipole ones.}. The ANL and BNL collaborations considered also monopole and tripole axial FFs but the obtained fits were worse than the dipole ones.
measurements of $M_A$ report much larger values: K2K (oxygen, $Q^2 > 0.2 \text{ GeV}^2$) → $1.2 \pm 0.12$ [9]; K2K (carbon, $Q^2 > 0.2 \text{ GeV}^2$) → $1.14 \pm 0.11$ [10]; MINOS (iron, $Q^2 > 0 \text{ GeV}^2$) → $1.19 \pm 0.17$; MINOS (iron, $Q^2 > 0.3 \text{ GeV}^2$) → $1.26 \pm 0.17$ [11]; MiniBooNE (carbon, $Q^2 > 0 \text{ GeV}^2$) → $1.35 \pm 0.17$; MiniBooNE (carbon, $Q^2 > 0.25 \text{ GeV}^2$) → $1.27 \pm 0.14$ [12] (for completeness: NOMAD (carbon, $Q^2 > 0 \text{ GeV}^2$) → $1.07 \pm 0.07$ [13]).

The difference between MB and NOMAD measurements can hopefully be explained by different definitions of the CCQE signal. In the case of MB a sample of 2-subevents (Cherenkov light from muon and from decay electron) is analyzed and ejected protons are not detected. In the case of NOMAD 1-track (muon) and 2-tracks (muon and proton) samples of events are analyzed simultaneously. With a suitable chosen value of the formation zone parameter $\tau_0$ [14] values of $M_A$ extracted separately from both data samples are approximately the same.

More detailed characterization of CCQE scattering was given by the MB experiment in the form of double differential cross section in muon kinetic energy and opening angle. A subtraction of the background (CCQE-like but not CCQE events) was done in the way which was intended to be independent on Monte Carlo (NUANCE [15]) modelling of nuclear effects. A correction DATA/MC function was obtained based on the sample of events dominated by the pion production and then applied to MC background predictions. The shape of the correction function is not well understood but it has an important impact on the extracted value of $M_A$. The function quantifies a lack of precision in describing processes like pion absorption and this can have different effect on understanding of QE-like and SPP-like samples of events. One can also use the CCQE signal and the background together as the measurement of CCQE-like cross section, the observable which is in the minimal degree dependent on MC assumptions.

NUANCE implementation of the IA is based on the FG model which does not provide a realistic description of the nucleon momenta distribution. This motivated later axial mass fits done within more sophisticated nuclear models. The authors of [16] used spectral function [17] and made a fit to full double differential cross section data. The overall normalization error evaluated by MB as 10.7% was also taken into account. Butkevich [18] made a fit only to the $Q^2$ differential cross section data [19]. Both analysis produced similar results: Butkevich obtained $1.37 \pm 0.05$ and JSZ $1.34 \pm 0.06 \text{ GeV}$ (with the low-momentum cut $q_{\text{cut}} = 500 \text{ MeV/c}$, details in [16]).

**MULTINUCLEON EJECTION**

A possible theoretical mechanism which can explain the $M_A$ value discrepancy comes from the many-body nuclear model proposed more than 10 years ago [20] and developed later by Martini, Ericson, Chanfray and Marteau (MEChM model) [21]. The idea of the

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3. When $\tau_0$ is increased FSI effects become more suppressed. This makes the predicted number of 1-track events smaller and 2-track events - larger. Thus, the fitted value of $M_A$ from 2-track events becomes smaller and from 1-track events - larger.

4. Target nucleon is a solution of the self-consistent Dirac equation in the $\sigma - \omega$ theory and ejected nucleon is treated in RDWIA (Relativistic Distorted Wave Impulse Approximation). Short Range Correlations effects are also taken into account [18].
importance of the many-body contribution in neutrino interactions is even older and was presented by Magda Ericson [22]. The model in [22] discusses an appearance of the pion branch, a collective nucleus excitation which decays into a pair of nucleons.

MEChM is the non-relativistic model that includes QE and $\Delta$ production primary interactions, RPA corrections and local density effects. Its interesting feature is the evaluation (without meson exchange current contribution) of elementary 2p-2h and 3p-3h excitations which lead to multinucleon ejection. This contribution is absent in free nucleon neutrino reaction. However, the evaluation of the np-nh contribution was based on approximate arguments and the authors of [21] admitted that a detail microscopic computation was missing. Within the MEChM model the new contribution is shown to be able to account for the large CCQE cross-section as measured by the MB collaboration.

In the case of neutrino-carbon CCQE process (after averaging over the MB neutrino beam) the nuclear effects are expected to increase the cross-section from 7.46 to 9.13 (in the units of $10^{-39}\text{cm}^2$ per neutron). This includes the cross-section reduction due to RPA effects and a substantial increase due to np-nh contribution. It is interesting that in the case of antineutrino-carbon CCQE scattering, because a relative significance of the isovector contribution is larger, RPA and 2p-2h effects cancel each other and the flux averaged cross-section remains virtually unchanged (modification from 2.09 to 2.07 in the units of $10^{-39}\text{cm}^2$ per proton).

Shortly before the NuInt11 Workshop the microscopic many-body evaluation of multinucleon ejection contribution was reported in the paper [23]. The computations were done in the theoretical scheme which is known to be successful in describing electron scattering in the kinematical region of QE and $\Delta$ excitation peaks together with the DIP region between them [24]. The model of [23] includes medium polarization effects and $\pi$ and $\rho$ meson exchange contributions in the vector-iso-vector channel. For neutrino scattering predictions of [23] and [21] are in good agreement. However, [23] predicts a substantial increase of the cross-section also in the case of antineutrino scattering, contrary to [21].

**RECENT EXPERIMENTAL DEVELOPMENTS**

During NuInt11 Workshop some new (usually preliminary) experimental results were presented. MINOS devoted [25] much effort on better evaluation of the pion production background. A function of $Q^2$ which corrects Monte Carlo (NEUGEN) RES (resonance production region) predictions was proposed. The shape of the curve is similar to MiniBooNE’s DATA/MC correction function but in the case of MB for $Q^2 > 0.1\text{GeV}^2$ the correction factor is $> 1$. The new MINOS best fit value of $M_A$ is 1.16 GeV and the error was reduced by a factor of 3.

SciBooNE showed [26] partial results of the CCQE analysis. Results are given in terms of fits for CCQE cross-section DATA/MC multiplicative factors $a_j$ ($j$ corresponds to true neutrino energy bins) and also an overall rescaling factor $F_N$. The obtained best fit values in the region $E \in (0.6, 1.6)\text{ GeV}$ are between 1.00 and 1.09 which with $F_N = 1.02$ and the value of the axial mass used in the NEUT Monte Carlo generator (1.2 GeV) will most likely translate to the axial mass value $M_A \sim 1.25 - 1.3\text{ GeV}$. The problem with SciBooNE measurement is that there are some instabilities in the wider range of neutrino
energies (see Fig. 11.2 in [27]). Also a use of only one universal background rescaling factor $a_{bcg}$ for three quite different event samples seems worrying, particularly because its best fit value is quite large (1.37).

An important antineutrino CCQE measurement was reported by the MiniBooNE [28]. The DATA/MC average cross-section ratio was measured to be $1.21 \pm 0.12$ which is a surprising result because in the NUANCE carbon CCQE $M_A$ value was 1.35 GeV. This results (if confirmed) may indicate that the treatment of multinucleon ejection contribution presented in the paper [23] is more accurate. In the experimental analysis it was very important to evaluate correctly a contribution from neutrino contamination in the anti-neutrino flux. Three independent measurements indicate that the $\nu_\mu$ flux should be scaled down by a factor of $\sim 0.8$ with an important impact on the final results.

Preliminary results from the MINERvA experiment [29] with antineutrino beam indicate that events distribution in $Q^2$ is slightly below MC predictions (GENIE with $M_A = 0.99$ GeV). However, one cannot say that there is no large $Q^2$ surplus of CCQE-like events because this region is strongly dominated by RES and DIS dynamics.

**SOLUTION OF THE AXIAL MASS PUZZLE?**

In the very recent paper [30] the model described in [23] was applied to MB double differential cross section data and a fit to the axial mass value was done. Strictly speaking the model used in the statistical analysis was the one presented in [31] because being a relativistic one it is more reliable in the whole kinematical region of the MB experiment. The model does not include FSI diagrams which can introduce modifications of the size of $\sim 7\%$. In the fitting procedure (taken from [32] and used also in [16]) the authors included an overall 10.7% normalization error. The two-parameter fit gave results: $M_A = 1.077 \pm 0.027$ GeV and for the normalization scale: $\lambda = 0.917 \pm 0.029$. It is interesting that with the low-momentum cut procedure, as proposed in [16], with $q_{cut} = 400$ MeV the value $M_A = 1.007 \pm 0.034$ GeV was obtained which is even closer to the historical world average.

**CONCLUSIONS**

A discussion of CCQE neutrino interaction on nuclear targets becomes quite complicated because it is necessary to consider the multinucleon ejection contribution both on experimental and theoretical levels. It seems that on the theoretical side the situation becomes clear and there are computations which show that the multinucleus ejection confused with genuine CCQE events can lead to large $M_A$ measurements. It is important that as the cross-check the same models are confronted with precise electron scattering data in kinematical regions similar to that of the MB experiment. In order to provide an experimental verification of the multinucleon ejection mechanism it is necessary to implement the models in MC event generators used by experimental groups and find predictions for kinetic energy of ejected nucleons which can be confronted with observables like the vertex activity.
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