Resolving the Axial Mass Anomaly in $\nu_\mu$ Scattering

A. Bodek*, H.S. Budd* and M. E. Christy†

*Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627-0171 USA
†Hampton University; Hampton, Virginia, 23668 USA

Abstract. We present a parametrization of the observed enhancement in the transverse electron quasielastic (QE) response function for nucleons bound in carbon as a function of the square of the four momentum transfer ($Q^2$) in terms of a correction to the magnetic form factors of bound nucleons. The parametrization should also be applicable to the transverse cross section in neutrino scattering. If the transverse enhancement originates from meson exchange currents (MEC), then it is theoretically expected that any enhancement in the longitudinal or axial contributions is small. We present the predictions of the “Transverse Enhancement” model (which is based on electron scattering data only) for the $\nu_\mu, \bar{\nu}_\mu$ differential and total QE cross sections for nucleons bound in carbon. The $Q^2$ dependence of the transverse enhancement is observed to resolve much of the long standing discrepancy (“Axial Mass Anomaly”) in the QE total cross sections and differential distributions between low energy and high energy neutrino experiments on nuclear targets.

Keywords: Neutrino interactions, Electromagnetic form factors, Quasielastic Scattering, Axial mass.

PACS: 13.15.eG; 25.30.Pt. [Presented by A. Bodek at PANIC 2011, MIT, Cambridge, MA. July 2011]

Models which assume that $\nu_\mu, \bar{\nu}_\mu$ quasielastic (QE) scattering on nuclear targets can be described in terms of scattering from independent nucleons bound in a nuclear potential (e.g. Fermi gas or spectral functions) do not provide an adequate representation of measured differential and total QE cross sections for low energy ($\approx 1$ GeV) $\nu_\mu$ scattering on nucleons bound in carbon (MiniBooNE) and oxygen (K2K and T2K). The measured QE total cross sections are 20-30% larger than the model and the differential distributions in $Q^2$ are also inconsistent. The vector and axial form factors that are used in “independent nucleon” models are the free nucleon form factors extracted from electron and $\nu_\mu, \bar{\nu}_\mu$ scattering data on hydrogen (H) and deuterium (D).

The disagreement between the measured low energy $\nu_\mu$ differential and total QE cross sections on nuclear targets and the predictions of the “independent nucleon” model has been attributed to an incomplete description of nuclear effects. These additional nuclear effects have been parametrized as an ad-hoc change in the axial form factor mass parameter from the value measured for free nucleons $M_A^{\text{free}} = 1.014 \pm 0.014$ GeV to $M_A^{\text{eff}} \approx 1.30$ GeV.

However, at high neutrino energies, the measured total and differential QE cross sections on nuclear targets are consistent with models which assume that the scattering is on independent nucleons with free nucleon form factors. For example, $M_A$ of 0.979 $\pm 0.016$ GeV has been extracted by Kuzmin et al. from a global analysis of the differential distributions and total QE cross sections measured in all high energy $\nu_\mu, \bar{\nu}_\mu$ experiments on nuclear targets. This discrepancy between low energy and high energy data has sometimes been referred to as the axial mass anomaly.

Studies of QE electron scattering on nuclear targets indicate that only the longitudinal part of the QE cross section can be described in terms of a universal response function of independent nucleons bound in a nuclear potential (and free nucleon form factors). In contrast, a significant additional enhancement with respect to the model is observed in the transverse part of the QE cross section.

The enhancement in the transverse QE cross section has been attributed to meson exchange currents (MEC) in a nucleus. In MEC models the enhancement is primarily in the transverse part of the QE cross section, while the enhancement in the longitudinal QE cross section is small. The conserved vector current hypothesis (CVC) implies that the corresponding vector structure functions for the QE cross sections in $\nu_\mu, \bar{\nu}_\mu$ scattering can be expressed in terms of the structure functions measured in electron scattering on nuclear targets. Therefore, there should also be a vector transverse enhancement in $\nu_\mu, \bar{\nu}_\mu$ scattering. In addition, in meson exchange currents models, the enhancement in the axial part of the $\nu_\mu, \bar{\nu}_\mu$ QE cross section on nuclear targets is also small. Therefore, the axial form factor for bound nucleons is expected to be the same as the axial form factor for free nucleons.

The longitudinal and transverse response functions for QE scattering on different nuclei ($A=12, 40$ and $56$) were extracted by Donnelly et al for $Q^2$ values of 0.09, 0.15, and 0.33 (GeV/c)². Carlson et al. use these measured longitudinal and transverse response functions to extract $R_T$, which is the ratio of the integrated transverse and the integrated longitudinal response functions (assuming free nucleon form factors). Since the universal longitudinal
Preliminary E04-001, E = 4.629, \( Q^2 = 0.68 \text{ (GeV/c)}^2 \)

FIGURE 1. Left: Example of the fit to preliminary electron scattering data from the JUPITER collaboration (Jefferson Lab experiment E04-001) on a carbon target. Shown are the contributions from the transverse QE (solid pink), longitudinal QE (dashed pink), total QE (solid red), inelastic pion production processes (solid green), and the transverse excess (TE) contribution (solid black line). Here, \( Q^2 = 0.68 \text{ GeV/c}^2 \) at the QE peak. Right: The transverse enhancement ratio \( \mathcal{R}_T \) as a function of \( Q^2 \). Here, \( \mathcal{R}_T \) is ratio of the integrated transverse response function for QE electron scattering on nucleons bound in carbon divided by the integrated response function for independent nucleons. The black points are extracted from Carlson et al, and the blue bands are extracted from the fit to QE data from the JUPITER collaboration. The curve is a fit to \( \mathcal{R}_T(Q^2) \) of the form \( \mathcal{R}_T = 1 + A Q^2 e^{-Q^2/B} \), with \( A = 6.0 \) and \( B = 0.34 \) (GeV/c)^2. The dashed lines are estimated upper and lower error bands.

response function can be described by a model of independent nucleons bound in a nuclear potential, \( \mathcal{R}_T \) is equivalent to the ratio of the transverse cross sections of bound and free nucleons.

We extract the transverse enhancement at higher values of \( Q^2 \) from a fit to existing electron scattering data on nuclei and preliminary data from the JUPITER collaboration (Jefferson Lab experiment E04-001). The fit (developed by P. Bosted and V. Mamyan) provides a description of inclusive electron scattering cross sections on a range of nuclei with \( A > 2 \). An example of the fit for a carbon spectrum is shown on the left panel of Fig.1.

The Bosted-Mamyan inclusive fit is a sum of four components:

- The longitudinal QE contribution extracted from H and D experiments (smeared by Fermi motion in carbon)
- The transverse QE contribution extracted from H and D experiments (smeared by Fermi motion in carbon)
- The contribution of inelastic pion production processes from H and D (smeared by Fermi motion in carbon).
- A transverse excess (TE) contribution (determined by the fit)

The right panel of Fig. 1 shows the values of \( \mathcal{R}_T \) as a function of \( Q^2 \). The black points are extracted from Carlson et al, and the higher \( Q^2 \) blue bands are from the fit to the QE data from the JUPITER collaboration. The data are parametrized by the expression: \( \mathcal{R}_T = 1 + A Q^2 e^{-Q^2/B} \) with \( A = 6.0 \) and \( B = 0.34 \) (GeV/c)^2. The electron scattering data indicate that the transverse enhancement is maximal near \( Q^2 = 0.3 \) (GeV/c)^2 and is small for \( Q^2 \) greater than 1.5 (GeV/c)^2. The dashed lines are the estimated upper and lower error bands.

Fig. 2 shows \( d\sigma/dQ^2 \) predictions for \( \nu \mu \) QE scattering on carbon as a function of \( Q^2 \). Shown are predictions of the "Independent Nucleon" model with \( M_A=1.014 \text{ GeV} \) (orange dotted line), with \( M_A=1.3 \text{ GeV} \) (blue dashed line), and with \( M_A=1.014 \text{ GeV} \) including "Transverse Enhancement" (red line). The left panel is for \( E_\nu = 1 \text{ GeV} \) and the right panel is for \( E_\nu = 3 \text{ GeV} \).

For \( Q^2 < 0.6 \) (GeV/c)^2 the predictions for \( d\sigma/dQ^2 \) with \( M_A=1.014 \) GeV and including "Transverse Enhancement" are similar to \( d\sigma/dQ^2 \) with \( M_A=1.3 \) GeV. The maximum accessible \( Q^2 \) for 1 GeV neutrinos is 1.3 (GeV/c)^2. Therefore, fits to \( d\sigma/dQ^2 \) for \( E_\nu = 1 \text{ GeV} \) (e.g. MiniBooNE) would yield \( M_A \approx 1.2 \) GeV.

In the high \( Q^2 \) region (\( Q^2 > 1.2 \) (GeV/c)^2), the magnitude of the "Transverse Enhancement" is small. The maximum accessible \( Q^2 \) for 3 GeV neutrinos is 4.9 (GeV/c)^2. In order to reduce the sensitivity to modeling of Pauli blocking, experiments at higher energy typically remove the lower \( Q^2 \) points in fits for \( M_A \). Consequently, fits to \( d\sigma/dQ^2 \) measured in high energy experiments would yield a value of \( M_A \) which is smaller than 1.014 GeV because for
$Q^2 > 0.5 \text{ (GeV/c)}^2$ the slope of $d\sigma/dQ^2$ in the transition region between low and high $Q^2$ is steeper than for $M_A=1.014$ GeV. This is consistent with the fact that the average $M_A$ extracted from high energy neutrino experiments on nuclear targets by Kuzmin et al. is $0.979 \pm 0.016$.

Fig. 3 shows the predictions for the $\nu_\mu$ (left) and $\bar{\nu}_\mu$ (right) total QE cross section as a function of $E_\nu$ for the "Independent Nucleon" model with $M_A=1.014$ GeV and $M_A=1.3$ GeV , compared to the "Independent Nucleon" model with $M_A=1.014$ GeV and "Transverse Enhancement" (with error bands). Also shown are predictions of "QE+np-nh RPA" Meson Exchange Current model of Martini et al. (Predictions for this model have only been published for $E_\nu < 1.2$ GeV). The data points are the measurements of MiniBooNE and NOMAD.

The predictions of the "Independent Nucleon" model with $M_A=1.014$ GeV including "Transverse Enhancement" are in agreement with the MiniBooNE cross sections at low energies, and are also consistent with the NOMAD cross section measurements at high energies (within experimental errors), thus resolving the "axial mass anomaly".

Additional details and a list of references discussed in this paper can be found in A. Bodek, H. S. Budd, M. E. Christy, "Neutrino Quasielastic Scattering on Nuclear Targets: Parametrizing Transverse Enhancement (Meson Exchange Currents)" arXiv:1106.0340 [hep-ph], and references therein.