Neutrino interactions with nucleons and nuclei at intermediate energies

L. Alvarez-Ruso, T. Leitner and U. Mosel

Institut für Theoretische Physik, Universität Giessen, Germany

Abstract. We investigate neutrino-nucleus collisions at intermediate energies incorporating quasielastic scattering and $\Delta(1232)$ excitation as elementary processes, together with Fermi motion, Pauli blocking and mean-field potentials in the nuclear medium. A full coupled-channel treatment of final state interactions is achieved with a semiclassical BUU transport model. Results for inclusive reactions and nucleon knockout are presented.

Keywords: neutrino-nucleus interactions, quasielastic scattering, Delta excitation, nucleon knock-out
PACS: 25.30.Pt, 24.10.Lx, 24.10.Jv, 14.20.Dh, 14.20.Gk, 13.15+g

The study of neutrino interactions with nucleons and nuclei is crucial for current and future oscillation experiments. The main goal is to improve our knowledge of the fluxes, backgrounds and detector responses in order to minimize systematic uncertainties. The availability of a high intensity ν beam at Fermilab offers as well a unique opportunity to gain new information on the structure of the nucleon and baryonic resonances. Experiments such as MINERνA and FINeSSE shall address relevant problems like the extraction of the nucleon and $N-\Delta$ axial form factors (FF), or the measurement of the strange spin of the nucleon. However, those experiments will be performed mainly on nuclear targets. Understanding nuclear effects is essential for the interpretation of the data and represents both a challenge and an opportunity.

We have developed a theoretical model of ν-nucleus collisions at energies between 0.5 and 2 GeV, where the dominating processes are quasielastic scattering (QE) and $\Delta(1232)$ resonance excitation. The model includes all ν flavors for both charged- and neutral-current processes in any *heavy* nucleus (from ^{12}C on). Here we focus on the ν_μ charged-current reaction on an iron target. Further details can be found in Ref. [1].

We describe ν-nucleon interactions in a fully relativistic formalism, using state-of-the-art parameterizations of the FF. The hadronic current in the QE case is given by

$$\langle p|J^\alpha|n\rangle = \cos\theta_C\,\bar{u}_p\left[F_1^V\left(\gamma^\alpha - \frac{\not{q}\,q^\alpha}{q^2}\right) + F_2^V\frac{i\sigma^{\alpha\beta}q_\beta}{2m_N} + F_A\gamma^\alpha\gamma_5 + F_P\frac{q^\alpha\gamma_5}{m_N}\right]u_n\,. \quad (1)$$

Written in this way, the vector part of the current is conserved even if the masses of the initial and final nucleons differ. This is an issue in the nuclear case, where the nucleons have momentum and density dependent effective masses. For the vector FF $F_{1,2}^V = F_{1,2}^p - F_{1,2}^n$, we take the parameterization of Ref. [2] (BBA-2003), which uses recent e^- scattering data from JLab to account for deviations from the dipole Q^2 dependence . The axial FF is given by the standard ansatz $F_A = g_A\left(1+Q^2/M_A\right)^{-2}$, with

$g_A = -1.267$ and $M_A = 1$ GeV; F_P can be related to F_A assuming PCAC.

The $N-\Delta(1232)$ transition current involves a larger number of FF

$$\langle\Delta|J^\alpha|N\rangle = a\cos\theta_C \bar{\psi}_\beta D^{\beta\alpha} u_N\,, \tag{2}$$

with $a=\sqrt{3}(1)$ for the $p-\Delta^{++}(n-\Delta^+)$ transition; ψ_β is a Rarita-Schwinger spinor and

$$\begin{aligned} D^{\beta\alpha} &= \left[\frac{C_3^V}{m_N}(g^{\alpha\beta}\not{q} - q^\beta\gamma^\alpha) + \frac{C_4^V}{m_N^2}(g^{\alpha\beta}q\cdot p' - q^\beta p'^\alpha) + \frac{C_5^V}{m_N^2}(g^{\alpha\beta}q\cdot p - q^\beta p^\alpha)\right]\gamma_5 \\ &\quad + \frac{C_3^A}{m_N}(g^{\alpha\beta}\not{q} - q^\beta\gamma_\alpha) + \frac{C_4^A}{m_N^2}(g^{\alpha\beta}q\cdot p' - q^\beta p'^\alpha) + C_5^A g^{\alpha\beta} + \frac{C_6^A}{m_N^2}q^\beta q^\alpha\,. \end{aligned} \tag{3}$$

The M1 dominance of the electromagnetic $N-\Delta$ transition implies that $C_5^V = 0$ and $C_4^V = -(m_N/W_\Delta)C_3^V$. For the remaining independent FF, we adopt a parameterization which describes pion electroproduction data [3]

$$C_3^V = C_3^V(0)\left(1+\frac{Q^2}{M_V^2}\right)^{-2}\left(1+\frac{Q^2}{4M_V^2}\right)^{-1} \tag{4}$$

with $C_3^V(0) = 1.95$ and $M_V = 0.84$ GeV. In the axial sector, the available information comes from bubble chamber experiments performed at ANL and BNL. The fits adopted the Adler model where $C_3^A = 0$ and $C_4^A = -C_5^A/4$. For C_5^A we have taken, as in Ref. [3],

$$C_5^A = C_5^A(0)\left(1+\frac{Q^2}{M_A^2}\right)^{-2}\left(1+\frac{Q^2}{3M_A^2}\right)^{-1} \tag{5}$$

where $C_5^A(0) = 1.2$ and $M_A = 1.05$ GeV. Finally, C_6^A can be written in terms of C_5^A via PCAC as in the QE case. The correct Δ invariant mass distribution is implemented by means of a spectral function with an energy dependent p-wave decay width.

When the reactions $\nu_\mu\, n \to p\,\mu^-$ and $\nu_\mu\, p(n) \to \Delta^{++}(\Delta^+)\,\mu^-$ take place in a nucleus, the initial nucleons have a finite momentum within a density dependent Fermi sea. The final nucleons can be Pauli blocked. This does not affect the Δ's directly, but its decay is inhibited due to the Pauli blocking of the nucleons that are produced in $\Delta \to N\pi$. On the other side, the decay into particle-hole states causes additional broadening [4]. We take also into account that nucleons and Δ's are bound in mean-field nuclear potentials and acquire, therefore, momentum and density dependent effective masses.

The double-differential cross section for the inclusive reaction $\nu_\mu\,{}^{56}Fe \to X\,\mu^-$ is shown in Fig. 1 as a function of the neutrino energy and the 4-momentum transfer at a fixed energy of the outgoing muon. At low Q^2 one can clearly distinguish two peaks associated with QE scattering (at lower energies) and Δ excitation. As Q^2 increases, the peaks get broader and overlap, while the cross section tends to zero.

In order to describe exclusive channels, final state interactions (FSI) have to be managed. This is achieved with a semiclassical BUU transport model in coupled channels (cf. [5]). The produced particles, moving along classical trajectories in the mean-field nuclear potential, can undergo elastic and inelastic collisions with the nucleons, decay (Δ's) or be absorbed (pions).

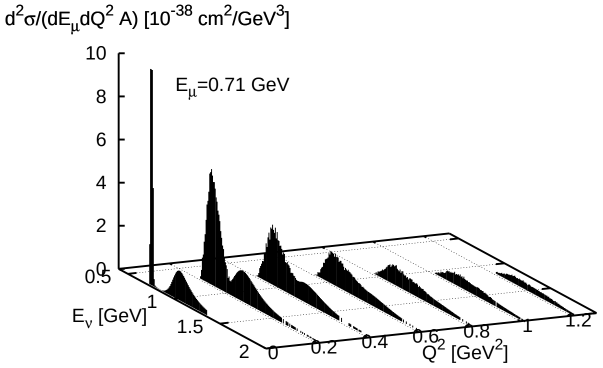

FIGURE 1. Cross section per nucleon for the inclusive process $\nu_\mu\,{}^{56}Fe \to X\,\mu^-$.

A first sample of our results for π production can be found in Ref. [6]. In Fig. 2 we present our distributions for p and n knockout as a function of the ν energy for fixed values of E_μ and Q^2. The overlaping QE and Δ peaks are clearly visible. As for QE, only

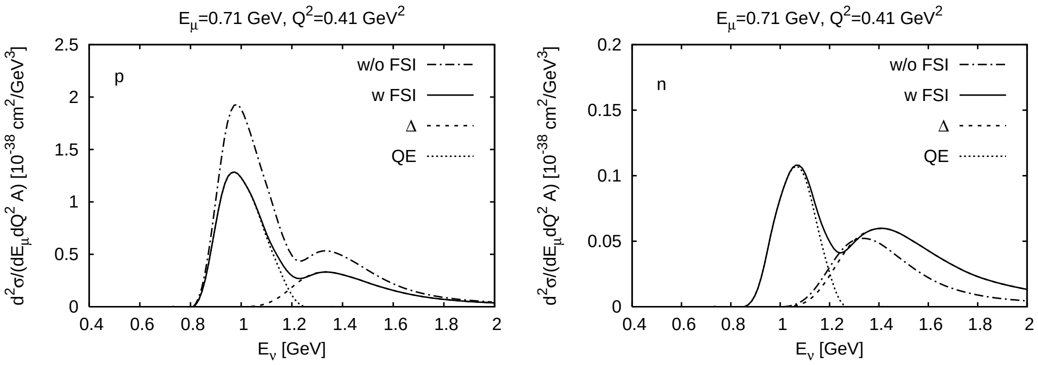

FIGURE 2. Proton and neutron knockout cross sections in charged-current $\nu_\mu\,{}^{56}Fe$ interactions.

p's can be produced in the initial collision; n's emerge only as a result of FSI processes. This explains the small cross section for n knockout and the reduction of the p one when FSI is considered. In the Δ region the situation is similar since only a small fraction of the neutrons comes directly from $\nu_\mu\, n \to \Delta^+\,\mu^- \to n\,\pi^+\,\mu^-$.

Work supported by the Deutsche Forschungsgemeinschaft.

REFERENCES

1. T. Leitner (2005), diploma thesis, http://theorie.physik.uni-giessen.de/documents/diplom/leitner.pdf.
2. H. Budd, A. Bodek, and J. Arrington (2003), `hep-ex/0308005`.
3. E. A. Paschos, J.-Y. Yu, and M. Sakuda, *Phys. Rev.* **D69**, 014013 (2004).
4. S. K. Singh, M. J. Vicente-Vacas, and E. Oset, *Phys. Lett.* **B416**, 23–28 (1998).
5. M. Effenberger, E. L. Bratkovskaya, and U. Mosel, *Phys. Rev.* **C60**, 044614 (1999).
6. T. Leitner, L. Alvarez-Ruso, and U. Mosel (2005), `nucl-th/0511058`.