GiBUU and Neutrino-Nucleus scattering

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Abstract. The Giessen BUU transport approach applied to electroweak interactions on nuclei in the few-GeV region is presented. After describing the model ingredients (elementary cross sections, medium effects and final state interactions), the impact of nuclear effects on the observables is discussed. We emphasize the interconnection of quasielastic and pion production processes, which receive a unified treatment, and its relevance for present neutrino experiments.

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INTRODUCTION

The Giessen Boltzmann-Uehling-Uhlenbeck project (GiBUU) provides a unified framework, based on the semiclassical transport model, for the description of various particle-nucleus reactions at a wide range of energies. GiBUU has been applied to hadron-nucleus (pA and πA) scattering and electromagnetic (photon and electron) interactions with nuclei. The GiBUU code was recently fully rewritten and released for public use. More information can be found in Ref. [1].

During the last 5 years, the model has been extended to the study of ν cross sections in the few-GeV region [2], where the major interest of ongoing neutrino oscillation experiments resides. These developments have led to predictions for the νA inclusive differential cross sections in the quasielastic and resonance regions and for exclusive channels like nucleon knock-out and pion production (πP), obtained without changing the nuclear physics input with respect to previous applications. This ensures that the knowledge gathered through extensive studies of hadronic interactions in the nuclear medium is taken into account in νA cross section research.

The GiBUU treatment of νA interactions consists of three ingredients: primary neutrino-nucleon interactions, modification of the elementary cross sections in the nuclear medium and propagation of the final state (FSI).

ELEMENTARY INTERACTIONS

We consider processes of the type $l(k)N(p) \rightarrow l'(k')X(p')$ where $X = N'$ for quasielastic scattering (QE) or $X = R$ for the excitation of 13 N^* and Δ resonances with $M_R < 2$ GeV. Nonresonant single πP ($X = N'\pi$) is also taken into account. Initial and final leptons can be chosen to describe charged current (CC), neutral current (NC) or electromagnetic (EM) processes. The differential cross section can be cast as [3]

$$\frac{d\sigma_X}{d\omega\, d\Omega_{k'}} = \frac{|\mathbf{k}'|}{32\pi^2} \frac{\mathscr{A}(p'^2)}{\left[(k\cdot p)^2 - m_l^2 M_N^2\right]^{1/2}} \overline{|\mathscr{M}_X|^2}, \quad (1)$$

where $\omega = q^0 = (k-k')^0$ is the energy transfered to the target and $\Omega_{k'}$ the solid angle of the outgoing lepton. For QE, $\mathscr{A}(p'^2) = \delta(p'^2 - M_N^2)$ and for resonance excitation,

$$\mathscr{A}(p'^2) = \frac{\sqrt{p'^2}}{\pi} \frac{\Gamma(p')}{(p'^2 - M_R^2)^2 + p'^2\Gamma^2(p')} \quad (2)$$

where $\Gamma(p')$ denotes the total decay width; $\overline{|\mathscr{M}_X|^2} = C L_{\mu\nu} H^{\mu\nu}$ with $C = 4\pi\alpha/q^2$, $G_F \cos\theta_C/\sqrt{2}$ and $G_F/\sqrt{2}$ for EM, CC and NC, respectively; $L_{\mu\nu}$ denotes the leptonic tensor. The hadronic tensor ($H^{\mu\nu}$) is determined by the current J_X^μ, parametrized by QE or $N-R$ transition form factors (FF). For spin $S = 1/2$ states $X = N$, $P_{11}(1440)$, $S_{11}(1535)$, $S_{31}(1620)$, $S_{11}(1650)$, $P_{31}(1910)$,

$$J^\mu_{\frac{1}{2}\{\pm\}} = u(p')\left[\frac{F_1}{(2M_N)^2}\left(\not{q}q^\mu - q^2\gamma^\mu\right) + \frac{F_2}{2M_N} i\sigma^{\mu\alpha}q_\alpha + F_A\gamma^\mu\gamma_5 + \frac{F_P}{M_N}q^\mu\gamma_5\right]\left\{\begin{array}{c}1\\ \gamma_5\end{array}\right\}u(p)\,, \quad (3)$$

and for $S = 3/2$ states $P_{33}(1232)$, $D_{13}(1520)$, $D_{33}(1700)$, $P_{13}(1720)$,

$$\begin{aligned} J^\mu_{\frac{3}{2}\{\pm\}} = u_\alpha(p')\Bigg[&\frac{C_3^V}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) \\ &+ \frac{C_4^V}{M_N^2}(g^{\alpha\mu}q\cdot p' - q^\alpha p'^\mu) + \frac{C_5^V}{M_N^2}(g^{\alpha\mu}q\cdot p - q^\alpha p^\mu) \\ &+ \Bigg(\frac{C_3^A}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^A}{M_N^2}(g^{\alpha\mu}q\cdot p' - q^\alpha p'^\mu) \\ &+ C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2}q^\alpha q^\mu\Bigg)\gamma_5\Bigg]\left\{\begin{array}{c}\gamma_5\\ 1\end{array}\right\}u(p)\,. \end{aligned} \quad (4)$$

The complication in the description of resonances with $S > 3/2$ [$D_{15}(1675)$, $F_{15}(1680)$, $F_{35}(1905)$ and $F_{37}(1950)$] is avoided by treating them as spin $3/2$ states. Their contributions are anyway negligible at 1-2 GeV. Obviously, for EM processes only terms with $F_{1,2}$ or C_i^V contribute, and these FF have been extracted from accurate electron scattering data. We have adopted the BBBA-2007 parametrization [4] for the nucleon while the resonance transition FF are expressed in terms of the helicity amplitudes obtained by the MAID analysis [5]. Isospin symmetry allows to relate the weak vector FF to the EM ones (see Table I of Ref. [3]). For the poorly known axial FF the strategy is to use PCAC and pion pole dominance to relate F_P to F_A (C_6^A to C_5^A) and to fix F_A (C_5^A) at $q^2 = 0$ in terms of the $R \to N\pi$ decay couplings (for the nucleon $F_A(0) = g_A$ is known from β decay). It is also assumed, following Adler, that $C_4^A = -C_5^A/4$ and $C_3^A = 0$. For the q^2 dependence of F_A and C_5^A a simple dipole ansatz is assumed

$$\left\{ \begin{array}{c} F_A(q^2) \\ C_5^A(q^2) \end{array} \right\} = \left\{ \begin{array}{c} F_A(0) \\ C_5^A(0) \end{array} \right\} \left(1 - \frac{q^2}{M_A^2}\right)^{-2} . \quad (5)$$

In the QE case we take the global fit of Ref. [6] to ν and $\bar{\nu}$ data $M_A = 0.999 \pm 0.011$ GeV and, in analogy, an $M_A = 1$ GeV is assumed for resonance excitation, with the exception of the $N - \Delta(1232)$. For the later, the q^2 dependence is fitted to $\nu_\mu\, p \to \mu^- \pi^+ p$ ANL data [3]. More recent determinations of this FF that take into account both ANL and BNL data, systematic errors in the ν fluxes, deuteron effects [7, 8] and the nonresonant background [8] but more precise νp data would be desirable.

Finally, the existence of important nonresonant contributions is well known. The vector part of the single pion background is obtained from the $eN \to e'N'\pi$ amplitudes in the MAID parametrization [5] after subtracting the resonance contribution. For the non-vector contribution, accounting for the axial part and interference, the same functional form of the vector background is assumed $d\sigma_{BG} = (1 + b^{\pi N}) d\sigma_{BG}^V$ with the constant $b^{\pi N}$ fitted to ANL data [3].

SCATTERING ON BOUND NUCLEONS

The neutrino-nucleon interactions discussed above are modified in the nuclear medium. Our description of bound nucleons is based on a Local Fermi Gas model: at each space point the initial-nucleon momentum distribution is given by a Fermi sphere $f(\mathbf{r},\mathbf{p}) = \Theta(p_F(r) - |\mathbf{p}|)$ with radius a $p_F(r) = [\frac{3}{2}\pi^2\rho(r)]^{1/3}$, with $\rho(r)$ the empirical nuclear density. A Pauli blocking factor for the outgoing nucleon $P_{\mathrm{Pauli}} = 1 - \Theta(p_F(r) - |\mathbf{p}|)$ also applies. All nucleons are exposed to a density and momentum dependent potential $V_N(\mathbf{p},\mathbf{r})$ whose parameters have been fixed by proton-nucleus scattering data [9]. The same potential is assumed for $S = 1/2, > 3/2$ resonances while for $S = 3/2$, it is approximated as $V_\Delta = 2/3 V_N$. As a consequence, baryons acquire effective masses $m_{\mathrm{eff}}(\mathbf{p},\mathbf{r})$ such that $\sqrt{\mathbf{p}^2 + m_N^2} + V(\mathbf{p},\mathbf{r}) = \sqrt{\mathbf{p}^2 + m_{\mathrm{eff}}^2}$.

The presence of interactions (NN and NR) inside nuclei leads to spectral functions

$$S(p) = -\frac{1}{\pi} \frac{\mathrm{Im}\Sigma(p)}{[p^2 - m_N^2 - \mathrm{Re}\Sigma(p)]^2 + [\mathrm{Im}\Sigma(p)]^2} . \quad (6)$$

As most of the nucleons in the nucleus can be described as occupying single-particle states in a mean field potential, we neglect NN interactions for the initial nucleons (holes) and take $\mathrm{Im}\Sigma = 0$ so that $S_h(p) \to \delta(p^2 - m_{\mathrm{eff}}^2)$. On the contrary, for the final baryons we consider interactions and take $\mathrm{Im}\Sigma = -\sqrt{(p^2)}\Gamma_{\mathrm{med}}(p,r)$; the in-medium width consists of the free width (of resonances) with Pauli blocking of the final nucleon, and collisional broadening $\Gamma_{\mathrm{coll}} = \rho\sigma_{NX}v_{\mathrm{rel}}$ fixed according to the GiBUU parametrizations. As for $\mathrm{Re}\Sigma$, it is obtained from $\mathrm{Im}\Sigma$ with a once-subtracted dispersion relation fixing the pole position at $p_0^{(\mathrm{pole})} = \sqrt{\mathbf{p}^2 + m_{\mathrm{eff}}^2}$ [3].

With the ingredients outlined so far it is possible to compute inclusive differential cross sections. In Fig. 1 the double-differential cross section for inclusive electron scattering on ^{16}O are compared to data. Results for other kinematics as well as predictions for the weak CC case can be found in Figs. 9, 10 and 12 of Ref. [3]. The overall agreement is good, with the QE (left) and

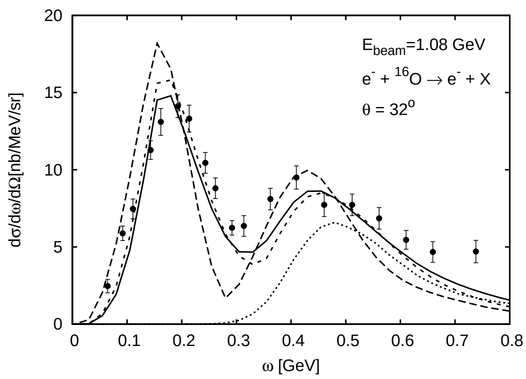

FIGURE 1. Inclusive electron scattering cross section on ^{16}O as a function of ω for a fixed beam energy and scattering angle. The full result is denoted by the solid line. Data are from Ref. [10].

$\Delta(1232)$ (right) peaks well described and the dip region in between slightly underestimated. The data are also underestimated at high ω due to the lack of 2π nonresonant background.

FINAL STATE INTERACTIONS

After the initial interaction, produced particles propagate through the nucleus undergoing FSI. This is simulated by means of a semiclassical transport model based on the BUU equations

$$(\partial_t + (\nabla_{\mathbf{p}} H)\nabla_{\mathbf{r}} - (\nabla_{\mathbf{r}} H)\nabla_{\mathbf{p}})\, f_i(\mathbf{r},\mathbf{p},t) = I_{\mathrm{coll}}\,[f_i, f_j] \quad (7)$$

which describes the evolution of the phase space density for each particle species $f_i(\mathbf{r},\mathbf{p},t)$ propagating in a mean field such that $H = \sqrt{m^2_{\mathrm{eff}}(\mathbf{p},\mathbf{r}) + \mathbf{p}^2}$. The BUU equations are coupled mainly through the collision term I_{coll} responsible for changes in f_i due to elastic and inelastic collisions as well as resonance formation and decay ($\pi N \to \pi N$, $NN \to NN$, $NN \leftrightarrow NR$, $NR \leftrightarrow NR'$, $R \leftrightarrow N\pi$). Notice that resonances are not only allowed to decay but also to interact with the medium. Nonresonant $\pi NN \to NN$ and resonant $\Delta NN \to NN$ three body channels are also included. All these processes are described in GiBUU using known hadronic properties and measured cross sections. Therefore, the framework allows to follow the propagating particles and make predictions for specific final states.

FSI leads to energy redistribution in the system, absorption and creation of new particles and charge exchange, causing considerable distortions in the observables. For example, pion kinetic energy spectra in CC production in nuclei $\nu A \to lX\pi$ are affected by strong absorption in the Δ region, pion energy loss due to rescattering, and side-feeding from the dominant π^+ to the π^0 channel (see Figs. 13, 14 of Ref. [11]).

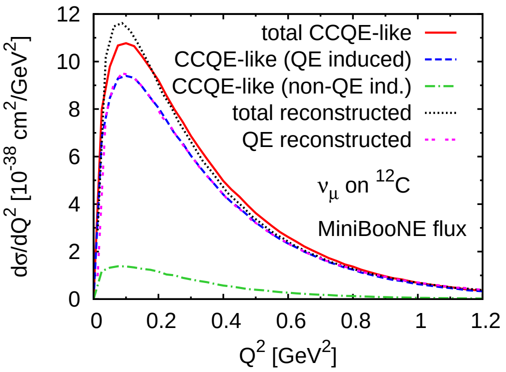

FIGURE 2. $d\sigma/dQ^2$ averaged over the MiniBooNE flux compared to reconstructed ones for CCQE (dashed and double-dashed lines) and for CCQE-like (solid and dotted) samples.

As a consequence of FSI, QE and πP in nuclei are interconnected. πP events where the pion is absorbed or undetected will be misclassified as QE. On the other side QE events where the outgoing nucleon hits another nucleon producing a pion $NN \to NN\pi$ will look as πP. The ability to isolate the CCQE sample in an experiment depends also on the detection technique and thresholds. A complete study of this problem with GiBUU was performed in Ref. [12]. It was found that ~ 20 % of the CCQE events are misidentified. This influences the ν energy reconstruction, unknown in experiments with broad band beams. Figure 2 shows the CCQE Q^2 distribution averaged over the MiniBooNE flux [13] compared to one reconstructed from the outgoing muon energy and angle assuming a QE collision with a single nucleon at rest. It turns out that the reconstruction procedure is almost perfect if performed on true CCQE events, but not if the whole CCQE-like sample is taken.

SUMMARY

GiBUU is a powerful tool for the description of particle-nucleus interactions that combines state-of-the-art hadronic input with medium effects and FSI. It has been successfully applied to strong and electromagnetic processes and recently extended to neutrino interactions without changing the nuclear parameters. Nuclear effects, required for a good description of inclusive EM data, are important. So are FSI for exclusive processes such as QE scattering and πP which are interconnected. A proper understanding and realistic description of these effects is crucial for the ongoing ν oscillation program.

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