HADRONIC TRANSPORT APPROACH TO NEUTRINO–NUCLEUS SCATTERING: THE GIESSEN BUU MODEL AND ITS VALIDATION*

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We present the GiBUU model for neutrino–nucleus scattering (νGiBUU): assuming impulse approximation, this reaction is treated as a two step process. In the initial state step, the neutrinos interact with bound nucleons. In the final state step, the outgoing particles of the initial reaction are propagated through the nucleus and undergo final state interactions. In this contribution, we focus on the validation of the initial and final state interaction treatment in GiBUU using experimental data for pion–nucleus, photon–nucleus and electron–nucleus scattering.

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1. Introduction

Present day long baseline experiments as MiniBooNE and K2K aim at a precise measurement of neutrino oscillations. The target material of most modern detectors consists of heavy nuclei such as carbon, oxygen and iron. To interpret their data, the experiments have to rely on Monte Carlo event generator predictions for the final state interactions (FSI) in the target nucleus. For an extraction of electroweak parameters from such experiments it is, therefore, important to know the expected accuracy of these Monte Carlo analyses. While most event generators are similar in their treatment of the initial neutrino–nucleon interaction, they differ significantly in their treatment of FSI (more details on the different models can be found in these proceedings). In addition, in most event generators, initial state and final state interactions are considered independently.

The Giessen Boltzmann–Uehling–Uhlenbeck (GiBUU) framework models the full space-time evolution of the phase space densities of all relevant particle species during a nuclear reaction within a consistent treatment of

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the initial vertex and the final state processes; and we emphasize that these should not be treated separately. This space-time evolution is determined by the so-called BUU equations, which describe the propagation of the particles in their potentials and also the collisions between them — resonances are treated explicitly. A major strength of the GiBUU model is that it has been applied to many different reactions from heavy ion collisions to pion and electron induced processes [1–4] (see Ref. [5] for more applications). The comparison with data for the reactions mentioned allows to make estimates for the expected accuracy in neutrino-induced reactions. Unlike most Monte Carlo event generators, we do not tune any specific input (like for example pion absorption cross-sections) to describe a specific reaction channel (like for example neutrino induced pion production). To the contrary, we include as much physics as possible and are thus in a position to explain simultaneously a wide range of very different reactions. In our understanding, these are the main points where we differ from event generators like NUANCE, NEUT and others.

In this contribution, we first introduce the GiBUU model focusing on issues relevant for neutrino–nucleus scattering. Then, we give examples for the applicability of our model and present results for pion-, photon- and electron-induced reactions which are confronted with experimental data. After this model validation, we give predictions for neutrino-induced pion production and nucleon knock-out.

2. Neutrino–nucleus scattering in the GiBUU model

In the GiBUU model, neutrino–nucleus scattering is treated as a two step process. In the initial state step, the neutrinos interact with nucleons embedded in the nuclear medium as explained in detail in Ref. [4]. The reaction products are, in the final state step, transported out of the nucleus using a hadronic transport approach [5]. We will give a brief introduction to both steps in the following.

We treat the nucleus as a local Fermi gas of nucleons bound in a mean-field potential and obtain for the total neutrino-induced cross-section on nuclei

$$d\sigma(\nu_\ell A \to \ell' X') = \int d^3r \int^{p_{\mathrm{F}}(r)} \frac{d^3p}{(2\pi)^3} \frac{k\cdot p}{k^0 p^0} d\sigma^{\mathrm{med}}_{\mathrm{tot}}(\nu_\ell N \to \ell' X) M_{X'} \,. \qquad (1)$$

In the latter equation, k is the four-vector of the neutrino, p the one of the bound nucleon, and $p_{\mathrm{F}}^{n,p}(r) = (3\pi^2 \rho^{n,p}(r))^{1/3}$ denotes the local Fermi momentum depending on the nuclear density. $M_{X'}$ is the multiplicity of the final state X' given an initial state X. This mapping $X \to X'$ is determined by the GiBUU transport simulation described below. The term $d\sigma^{\mathrm{med}}_{\mathrm{tot}}$ stands for the total cross-section on nucleons including nuclear medium corrections.

In the region of intermediate lepton beam energies ($E_{\rm beam} \sim 0.5$–2 GeV), the total lepton nucleon cross-section $d\sigma_{\rm tot}$ contains contributions from quasi-elastic scattering (QE: $\ell N \to \ell' N'$), resonance excitation (R: $\ell N \to \ell' R$) and direct, *i.e.*, non-resonant, single-pion production (BG: $\ell N \to \ell' \pi N'$) treated in our description as background. The single-pion region is strongly dominated by the excitation of the Δ resonance $P_{33}(1232)$, however, we include in addition 12 N^* and Δ resonances with invariant masses less than 2 GeV. The vector parts of the single contributions are obtained from recent analyses of electron scattering cross-sections. The axial couplings are obtained from PCAC (partial conservation of the axial current), and, wherever possible, we use neutrino–nucleon scattering data as input.

The neutrino–nucleon cross-sections are modified in the nuclear medium, *i.e.*, $d\sigma_{\rm tot} \to d\sigma_{\rm tot}^{\rm med}$. Bound nucleons are treated within a local Thomas–Fermi approximation which naturally includes Pauli blocking. The nucleons are bound in a mean-field potential depending on density and momentum which we account for by evaluating the above cross-sections with full in-medium kinematics. We further consider the collisional broadening of the final state particles within the low-density approximation $\Gamma_{\rm coll} = \rho \sigma v$ obtained in a consistent way from the GiBUU cross-sections (see below). Details of our model for the elementary vertex and the corresponding medium-modifications can be found in Ref. [4].

Once produced inside the nucleus, the particles propagate through the nucleus undergoing final state interactions (FSI) which are simulated with the coupled-channel semi-classical GiBUU transport model [5][1]. Originally developed to describe heavy-ion collisions, it has been extended to describe reactions of pions, photons, electrons, and neutrinos with nuclei [2–4].

This model is based on the BUU equation which describes the space-time evolution of a many-particle system in a mean-field potential. For particles of species i, it is given by

$$(\partial_t + \boldsymbol{\nabla}_p H \cdot \boldsymbol{\nabla}_r - \boldsymbol{\nabla}_r H \cdot \boldsymbol{\nabla}_p)\, f_i(\boldsymbol{r}, p, t) = I_{\rm coll}[f_i, f_N, f_\pi, f_\Delta, ...]\,, \qquad (2)$$

where the phase space density $f_i(\boldsymbol{r}, p, t)$ depends on time t, coordinates $\boldsymbol{r}$ and the four-momentum p. H is the relativistic Hamiltonian of a particle of mass M in a scalar potential U given by $H = \sqrt{[M + U(\boldsymbol{r}, p)]^2 + \boldsymbol{p}^2}$. The scalar potential U usually depends both on four-momentum and on the nuclear density. The collision term $I_{\rm coll}$ accounts for changes (gain and loss) in the phase space density due to elastic and inelastic collisions between the particles, and also due to particle decays into other hadrons. The BUU equations for all particle species are thus coupled through the collision term and also through the potentials in H. A coupled-channel treatment is

[1] The GiBUU code is available for download on our website [5].

required to take into account side-feeding into different channels. Baryon–meson two-body interactions (*e.g.*, $\pi N \to \pi N$) are dominated by resonance contributions and a small non-resonant background term; baryon–baryon cross-sections (*e.g.*, $NN \to NN$, $RN \to NN$, $RN \to R'N$, $NN \to \pi NN$) are either fitted to data or calculated, *e.g.*, in pion exchange models. The three-body channels $\pi NN \to NN$ and $\Delta NN \to NNN$ are also included. This complex set of coupled differential-integral equations is then solved numerically with the GiBUU code.

All particles (also resonances) are propagated in mean-field potentials according to the BUU equations. Those states acquire medium-modified spectral functions (nucleons and resonances) and are propagated off-shell. The medium-modification of the spectral function is based both on collisional broadening and on the mean-field potentials, both depending on the particle kinematics as well as on the nuclear density. With our off-shell transport we ensure that after leaving the nucleus, vacuum spectral functions are recovered. Finally, the final state multiplicity $M_{X'}$ is determined by counting all asymptotic particles X'.

We summarize that FSI lead to absorption, charge exchange and redistribution of energy and momentum, as well as to the production of new particles. Full details of the GiBUU model are given in Ref. [5] and references therein.

3. Model validation: pion and electron scattering

Before applying the above introduced transport model to neutrino–nucleus reactions, we first evaluate its quality by comparing its predictions for various experimentally accessible reactions to data. We restrict ourselves to electron- and photon-induced reactions on nuclei which are in the initial state similar to neutrino–nucleus reactions, and to pion-induced reactions which test our description of the $\pi N \Delta$ dynamics in nuclei directly.

Let us first focus on pion absorption on nuclei, which directly tests the pion FSI (for details *cf.* [3]). In Fig. 1 we show calculations for two different nuclei as a function of the pion energy for both, $\pi^\pm$. Comparing the curves obtained without any potential (dotted) to those with the Coulomb potential included (dashed), we see that the Coulomb potential is non-negligible in particular for heavier nuclei. We see a reduction of the cross-section for the π^+ and a large increase of the cross-section for the π^- meson. This agrees with the findings of Nieves *et al.* [8], who pointed out the relevance of the Coulomb potential in their quantum mechanical calculation of absorption and reaction cross-sections. When one, in addition, includes the hadronic potential for the pion (solid lines), it adds up with the Coulomb potential to a strongly repulsive potential in the case of a π^+, while, for the negative pion, at very low energies the two potentials can even compensate each other (in particular for light nuclei). Overall, we conclude, that the proper inclusion of the potentials is required to obtain good agreement with the data.

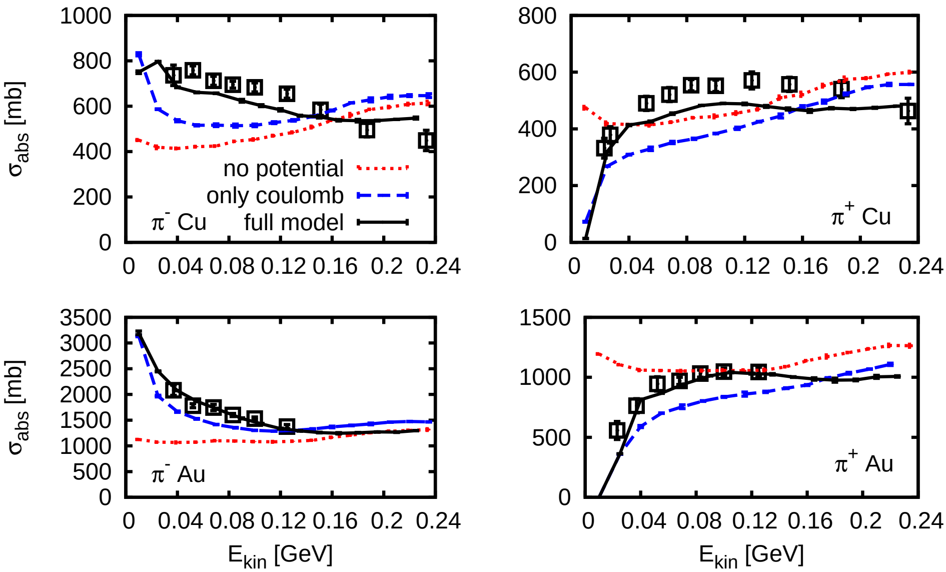

Fig. 1. Pion absorption on nuclei depending on the choice of potentials for the pion. The data points are taken from Ref. [7].

The BUU results for photon induced π^0 production, which directly test the vector-interaction part of ν-induced π^0 production, are shown in Fig. 2 for Ca, Nb and Pb nuclei for various photon energies as a function of the pion momentum. Good agreement with the TAPS data [9] is found, in particular the shape is reproduced (for further comparisons see Ref. [9]). Also the results without FSI (dashed lines) and the deuterium data (open circles) show very similar shapes. Comparing the dashed with the solid lines (results without FSI *versus* full calculation), one finds a considerable change of the spectra. This shape change is caused by the energy dependence of the pion absorption and rescattering cross-sections. Pions are mainly absorbed via the Δ resonance, *i.e.*, through $\pi N \to \Delta$ followed by $\Delta N \to NN$. This explains the reduction in the region around $p_\pi = 0.3$–0.5 GeV. In addition, pion elastic scattering $\pi N \to \pi N$ reshuffles the pions to lower momenta.

A promising test of the FSI strength is the transparency ratio in $A(e,e'p)$ reactions. It is defined as the ratio of protons leaving the nucleus with FSI to those without FSI. While the former quantity can be measured, the latter is purely theoretical and special assumptions have been made in the experimental analyses [10–12]. Fig. 3 shows the GiBUU result for the transparency ratio for different nuclei as a function of the four-momentum transfer Q^2. The agreement to data is perfect over the wide range of Q^2. For details we refer to Ref. [13].

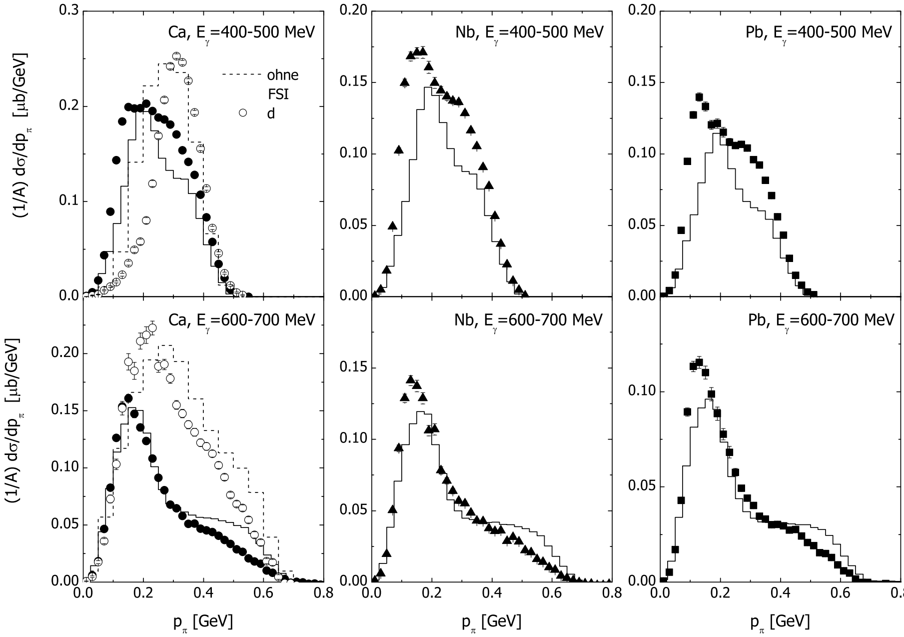

Fig. 2. Momentum differential cross-section for photon induced π^0 production for different nuclei and energies. For Ca also the results without FSI are shown (dashed curves) and compared to deuterium data (open circles). Data are from [9] (figure taken from Ref. [6]).

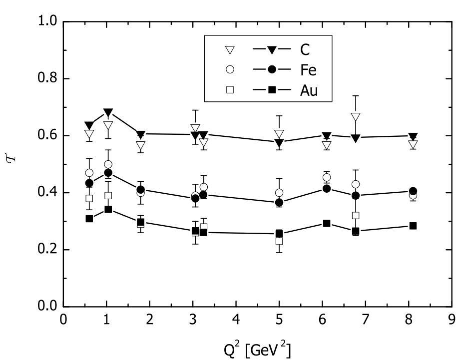

Fig. 3. Transparency ratio for C, Fe and Pb compared to data (open symbols) from JLab and SLAC [10–12]. The full symbols connected by the lines give the prediction of GiBUU (figure taken from Ref. [6]).

4. Application to neutrino scattering

To visualize the impact of FSI for neutrino induced reactions, we show in Fig. 4 the GiBUU results for NC π^0 production (left panels) and proton knockout (right panels) as a function of the corresponding kinetic energy averaged over the MiniBooNE (top; peaks at 0.7 GeV neutrino energy) and the K2K energy flux (bottom; peak at 1.2 GeV), respectively. The dashed line does not include neither FSI nor in-medium spectral functions; both are included in all the other lines. The dotted lines stand for a more inclusive result where the final state may contain more than a single-π^0/single-proton. This condition is applied in the solid lines where X may not contain any other pions or knocked out nucleons. Finally, the dash-dotted lines indicate the contribution of the initial Δ excitation to the solid line.

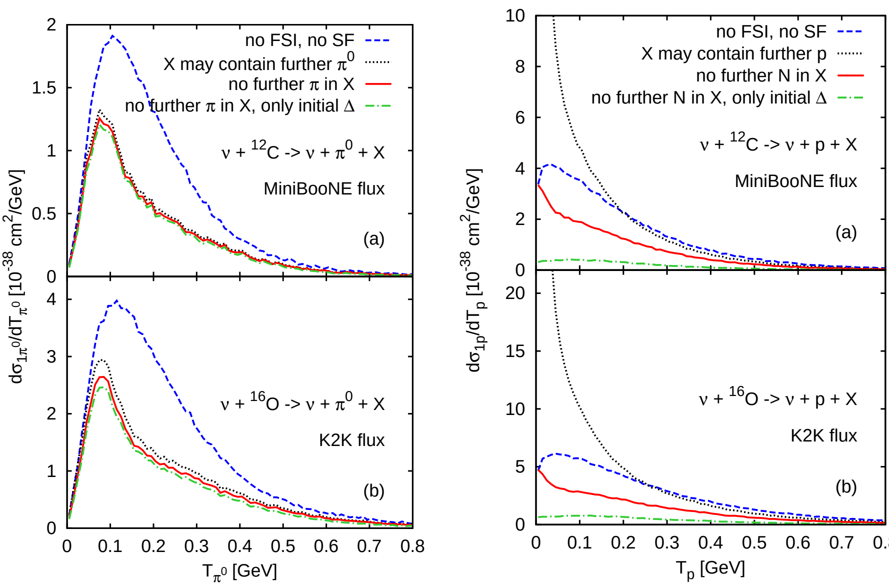

Fig. 4. Left panel: (a) NC induced π^0 production on ^{12}C as a function of the pion kinetic energy averaged over the MiniBooNE flux. (b) the same on ^{16}O averaged over the K2K flux. Right panel: the same for proton knockout.

As for the case of photoproduction discussed before we find a major impact of the FSI on the pion spectra (comparing dashed with the solid line in left panels). The vast majority of the pions come from initial Δ excitation (dash-dotted line). Both, the MiniBooNE and the K2K collaboration, have recently measured NC single-π^0 momentum spectra [14, 15], however, their data are only available as count rates and not yet as cross-sections. A direct and meaningful comparison to these measurements will be possible when acceptance corrected cross-sections are provided. Also for proton-knockout, FSI are not negligible, as already seen before in the transparency ratios. The rescattering leads in particular to a large number of knocked out protons at lower T_p (increase in dotted lines), or, if one looks at it more exclusively (single-proton knockout), a reduction of flux (dashed *versus* solid lines).

5. Conclusions

In this contribution, we have introduced the GiBUU model for neutrino–nucleus scattering with a focus on the FSI treatment. To validate our model, we have presented results for photon-, electron- and pion-induced reactions which exhibit similar features as neutrino-induced processes. We have emphasized that in particular the pion kinetic energy distributions are very sensitive to a realistic description of the $\pi N \Delta$ dynamics.

We conclude from the successful comparison of the GiBUU calculations for pion, photon and electron induced reactions to experimental data, that the treatment of initial and final state interactions is under good control and leads to reliable predictions. In this sense, the above comparisons serve as a direct benchmark for our neutrino calculations.

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