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ONE PION PRODUCTION IN NEUTRINO INDUCED REACTIONS*

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We investigate neutrino interactions with nucleons and nuclei, paying special attention to 1-pion production reactions. The elementary neutrino–nucleon cross-section is presented as the sum of the leading Delta-pole diagram and several background diagrams calculated within the non-linear sigma-model. Neutrino interactions with nuclei could then be treated within the GiBUU transport model that takes into account various nuclear effects.

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1. Introduction

The interest in one-pion production in neutrino–nucleus reactions has recently been revived in view of the current experimental search for neutrino oscillations. The neutrino energy spectra for the ongoing and coming long baseline neutrino experiments are typically peaked at a few GeV, the region where the one pion production along with the quasielastic (QE) scattering gives a major contribution. Besides being interesting as a separate channel, pion production constitutes a noticeable background for various processes: the produced pion can be absorbed in the nucleus and thus mimic a QE event, in Cherenkov detectors π^0 can mimic the outgoing electron. Thus, a precise knowledge of the corresponding cross-sections is a prerequisite for the proper interpretation of the experimental data.

Understanding of one-pion production includes two aspects: a proper description of the elementary process on nucleon and a proper treatment of the nuclear correction. Here we will concentrate on the elementary process and describe our approach.

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2. One-pion production as resonance and background contributions

In electromagnetic processes, the one pion production cross-section, being plotted *versus* the invariant mass of the outgoing pion and nucleon, is seen as a series of peaks. This picture was a basis for the so-called isobar models, in which the intermediate state of the reaction was treated as baryon resonance. The prominent one was shown to originate mainly from the Delta ($P_{33}(1232)$) excitation. The second broader peak receives contributions from the so-called second resonance region, which includes $P_{11}(1440)$, $D_{13}(1520)$ and $S_{11}(1535)$ resonances. In electroproduction the resonance excitations are known to be accompanied by the so-called non-resonance background, which can also interfere with the resonance contribution. The modern precise experiments on meson electroproduction, accompanied by the various amplitude analysis methods, allow the separation of those contributions and extraction of the information, related to the resonances only; see, for example, [1] for the review. That information can be expressed in the form of the quasi-experimental "data points" for the invariant helicity amplitudes, which characterize resonances and exclude background.

In neutrinoproduction, we extrapolate and extend the above picture and describe the one-pion production as a sum of the resonance and background contributions. The very possibility to fix the elementary neutrino–nucleon vertex relies on comparison of theoretical and/or phenomenological models with the experimental data, obtained in 80s in bubble chamber experiments. The most relevant ones are hydrogen and deuterium data from Argonne (ANL) and Brookhaven (BNL) National Laboratories. The experimental problem in neutrino experiments is that for those and all other experiments one cannot fix the neutrino energy, but has to use broad band neutrino beams. Besides, the number of neutrino events in the detector is very few (especially compared to electroproduction), so that only integrated and one-differential cross-sections were measured.

The theoretical description, being challenging in the case of electroproduction, is even more complicated for neutrino reactions, because in addition to the vector part we have the axial one and vector-axial interference. Thus, we are facing the problem of fixing both the background and the resonant part from a very restricted set of cross-sections. Within the phenomenological models, the way out of this situation was to presuppose that in the νp reaction, that is in the isospin-3/2 channel, there is no background for the Δ^{++} production. Thus, it was presupposed, that the one pion production in the region of $W < 1.4$ GeV is described by the pure isobar Δ amplitude with the following Δ decay. Within this picture (as soon as the vector form factors of the Δ production are considered to be fixed from electroproduction data), one can fit the Delta axial form factors and use them further for other channels. The recent progress in this direction was achieved in refitting the vector form factors from the up-to-date electroproduction data on helicity amplitudes [2] and refitting the axial form factors in the combined analysis of the ANL and BNL experiments [3].

Even in this picture we have to go beyond the isobar concept and include background contributions, when considering $p\pi^0$ and $n\pi^+$ final states. The simplest argument comes from the experimental observation that the cross-sections for the above two final states are approximately equal, while the Δ contribution gives $\sigma(p\pi^0)/\sigma(n\pi^+) = 2$. The calculated cross-sections are also shown to be lower than the experimental data. Including higher resonances, in particular the three isospin-1/2 states mentioned above, increases the cross-sections and improves the situation. For isospin-1/2 resonances $\sigma(p\pi^0)/\sigma(n\pi^+) = 1/2$, so that for the sum of the resonances the ratio is smaller than 2, but still not 1. The additional contributions required can be introduced within the same assumption $\sigma(p\pi^0)/\sigma(n\pi^+) = 1/2$, and thus are called "isospin-1/2" background [2]. The same philosophy was applied recently in [4], where the form of the background was extracted from electroproduction, as it is described by the MAID group, and then the magnitude of the background was fitted to the ANL data.

3. Background as sum over diagrams

Nowadays it becomes quite clear, that the simple picture of the background, described in the previous section, is mainly helpful in understanding the observables related to the outgoing lepton. However, it does not include the resonance-background interference, which would mainly change pion-related observables and, what is even more important, is not suitable for applying nuclear correction. The way beyond this simplest picture is treating the background as a sum of Feynman diagrams with pion and nucleon in the final state. The progress in this direction was achieved by Sato and Lee [5] and recently by Hernandez, Nieves and Valverde [6].

The diagrams considered are shown in Fig. 1. The principle feature of this picture is that it introduces the background not only for the $p\pi^0$ and $n\pi^+$ final states, but also for the $p\pi^+$, that is for the isospin-3/2 channel. In this sense, the result of [6], that in this channel the contribution of the background is at the level of less than 10%, is important and explains the applicability of the simple picture described above. Another principle feature of the model is that the dominant isobar channel is one of the diagrams considered ("Delta pole"), and thus the resonance-background interference is intrinsically included.

The main problem in this approach is that the diagrams considered in turn introduce new vertices, which have to be somehow fixed.

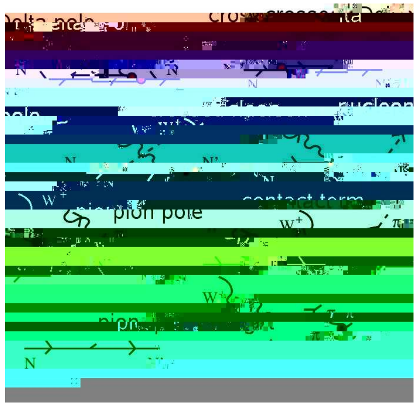

Fig. 1. Diagrams representing Δ pole and background contributions to the one pion production in weak charged current scattering on nucleon (taken from [6]).

The progress in understanding the background can only be achieved, if those vertices are considered as known and are constructed with no adjustable parameters. In the Sato–Lee model [5] they are calculated from the quark model and from the chiral Lagrangian of nucleon–meson interactions. In the HNV model [6] the vertices with a Δ are treated phenomenologically and other vertices are described within the SU(2) nonlinear sigma model in the leading order. The only phenomenological elements there include form factors for the "contact term" and "pion in flight" diagrams and account for ρ-meson dominance, which still do not require adjustable parameters.

4. Preliminary results

The model [6] is now being implemented into the GiBUU code. Our preliminary results for CC νp and νn reactions with one pion in the final state are shown in Fig. 2. For the neutron the two final states $p\pi^0$ and $n\pi^+$ are summed up. Presented is the double differential cross-section $d\sigma/dE_\mu d\cos\theta_\mu$ for the incoming neutrino energy $E_\nu = 1$ GeV and the muon scattering angle $\cos\theta_\mu = 0.6$ *versus* the energy E_μ of the outgoing muon. The form factors used are taken to be same as in [6]. For the proton target the background terms are indeed small in comparison with the pole contribution, while for the neutron target they are noticeable. The largest contribution (for the kinematics considered), according to our calculations, comes from the "contact term", whose contribution to the neutron target reaction is three times bigger than that for the proton target.

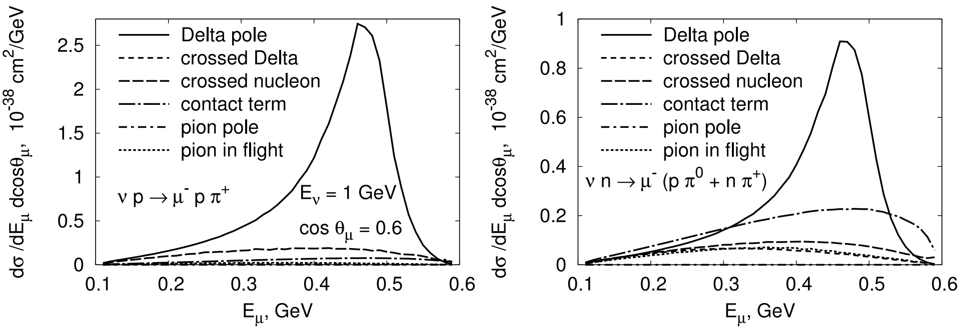

Fig. 2. Contribution of different diagrams to neutrino scattering on proton and neutron.

Figure 3 shows the same differential cross-section obtained as the coherent sum of all diagrams. It appears to be smaller than the incoherent sum of the contributions, which is also shown. Thus, for the kinematics considered, the interference effect is negative at E_μ below the Δ-peak, while it is positive at E_μ above the Δ-peak, which correspond to the low W, that is to the dip region between the QE and Delta peaks.

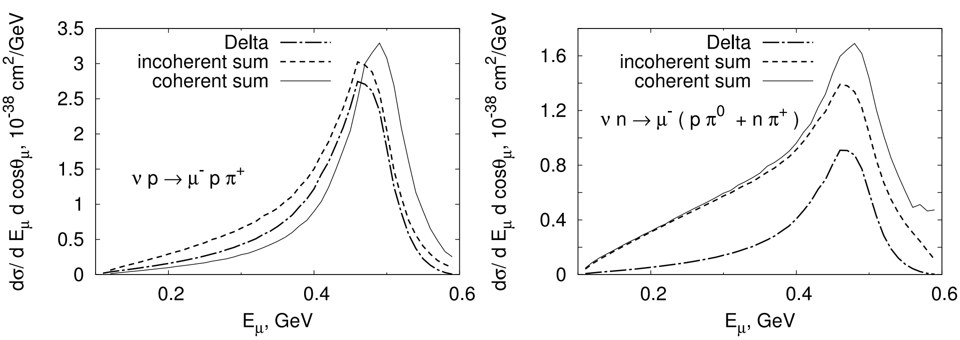

Fig. 3. Coherent and incoherent sum of the diagrams for neutrino scattering on proton and neutron targets.

Integrated cross-sections *versus* neutrino energy, as well as data from ANL and BNL experiments are shown in Fig. 4. These plots reveal the same general picture: background terms give only a small contribution to the cross-section on the proton target and are very important for the neutron target. One can notice, that our preliminary results do not exactly coincide with those from [6]. This point has still to be carefully examined and verified.

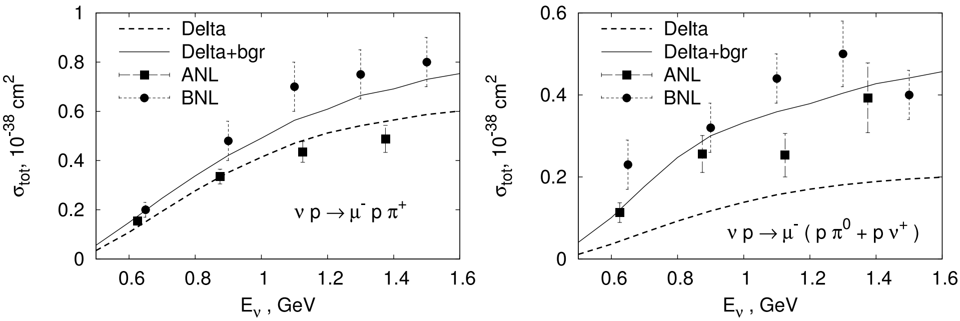

Fig. 4. Integrated cross-section for proton and neutron targets.

5. Outlook

As soon as the elementary vertex is fixed, the nuclear part can be treated within the GiBUU transport code.

The Giessen Boltzmann–Uehling–Uhlenbeck (GiBUU) transport model is a simulation code for hadron-, photon-, electron-, neutrino- and heavy-ion-induced reactions on nuclei. It is based on a coupled set of semiclassical kinetic equations which describe the dynamics of a hadronic system explicitly in phase space and in time. The initial state of the hadronic system is either directly corresponding to the experimental conditions (meson–nucleus, hadron–nucleus and heavy-ion collisions), or is obtained via external models (photon–, electron– and neutrino–nucleus reactions). The code is an open source code available on `http://gibuu.physik.uni-giessen.de/GiBUU/wiki/GiBUUSource`

The external model for the initial neutrino interaction already available is based on the isobar model of resonance excitations with a phenomenological background. The resonances, which further propagate in nuclear medium, can decay giving one pion or rescatter and produce pionless final states [4,7]. The model [6] is now being implemented into the GiBUU code as the second external model. Then, the description of the neutrino–nucleus reaction is straightforward.

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