Shallow-and-Deep Inelastic Scattering with Neutrinos

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In $\nu/\overline{\nu}$-Nucleon/Nucleus interactions Shallow Inelastic Scattering (SIS) is technically defined in terms of the four-momentum transfer to the hadronic system as non-resonant meson production with predominantly lower Q^2. This non-resonant meson production intermixes with resonant meson production in a regime of similar effective hadronic mass W of the interaction. As Q^2 grows non-resonant interactions begin to take place with quarks within the nucleon indicating the start of Deep Inelastic Scattering (DIS). To essentially separate this resonant plus non-resonant meson production from DIS quark-fragmented meson production, a cut of 2 GeV in W of the interactions is generally introduced. However, since experimentally mesons from resonance decay cannot be separated from non-resonant produced mesons, SIS for all practical purposes is defined as inclusive meson production that includes non-resonant plus resonant meson production and the interference between them. NOTE, this is a mildly modified introduction and overview taken from the detailed summary of this topic referenced in the introduction.

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1. Introduction

The following is an overview taken from the detailed summary of this subject (Neutrino(Antineutrino)-Nucleus Interactions in the Shallow-and Deep-Inelastic Scattering Regions) by M. Sajjad Athar (Aligarh Muslim University) and the present author [1]. The reader is directed to this comprehensive review for all relevant details.

In the energy range of accelerator-based and atmospheric neutrinos, the experimental study of neutrino physics is currently focused on understanding the three flavor ν_l oscillation phenomenology in the lepton sector of weak interactions. In particular an accurate measurement of any CP violation as well as determining the mass hierarchy of the three neutrino mass states is the goal of current and future neutrino oscillation experiments.

The experimental determination of these important properties depend on accurate knowledge of the energy (E_ν) of the interacting ν_l and the produced particles at the interaction point. However, ν_l oscillation experiments accelerator and atmospheric $\nu_l/\bar{\nu}_l$ have had to use moderate to heavy nuclear targets like ^{12}C, ^{16}O, ^{40}Ar and ^{56}Fe. This complicates the precision measurement of these properties since to obtain the initial energy and produced topology of the interacting neutrino, as opposed to the energy and topology measured in the detectors, model-dependent nuclear corrections, referred to as the "nuclear model", must be applied to the interpretation of the data. This nuclear model contains the current knowledge of the initial $\nu_l/\bar{\nu}_l$ - nucleon cross sections, the initial state nuclear medium effects and the final state interactions of the produced hadrons within the nucleus. The introduction of this nuclear model to the interpretation of experimental data is performed by Monte Carlo simulation programs (neutrino event generators) that apply these nuclear effects to the free nucleon interaction cross sections. Note that in this procedure, even before introducing uncertainties associated with the nuclear model [2]-[3], uncertainties are already introduced into the analysis due to the lack of precise knowledge of the ν_l *nucleon* interaction cross sections.

In the energy region of ≈ 1-10 GeV, covering present and future oscillation experiments, the final states are dominated by quasielastic(QE) scattering, resonant and non-resonant (mainly) π production and deep inelastic (DIS) scattering processes. Although these scattering processes are possible via charged(CC) as well as neutral(NC) current channels the referenced review, covers only the *charged current* interactions yielding a charged lepton in the final state and furthermore concentrates on the higher hadronic effective mass states that transition into and are within the deep-inelastic scattering regime. This transition region includes higher effective mass resonant and non-resonant single and multi-pion production.

1.1 Shallow-Inelastic Scattering

As indicated, when a ν_l or $\bar{\nu}_l$ interacts with a nucleon bound in a nuclear target, nuclear medium effects become important. These nuclear medium effects are energy dependent and moreover different for each interaction mode. In resonant and non-resonant production nuclear effects of the initial state such as Fermi motion, binding energy, Pauli blocking, multi-nucleon correlation effects have to be taken into account. In addition, final state interaction of the produced nucleons and pions within the nucleus are also very important. There are several theoretical calculations of these initial and final state nuclear medium effects in inelastic scattering where one pion is produced [4]-[5]. However, as summarized in a white paper from NuSTEC [6], there are very limited studies of

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multi-π resonant production and the other shallow inelastic scattering (SIS) processes such as non-resonant π production and the resulting interference of resonant/non-resonant states in the weak sector.

The importance of non-resonant meson production and the resulting interference effects with resonant production is receiving renewed emphasis since there are efforts underway to produce more theoretically-based estimates [7, 8] of these processes rather than the phenomenological approach of extrapolating the DIS cross sections to lower hadronic mass W used in some MC generators [10, 15]. As emphasized before, this kinematic regime as both the non-resonant meson production and the resonant region transitions into the DIS region can only be studied in terms of inclusive production for example, by Morfín et al. [11], Melnitchouk et al. [12], Lalakulich et al. [13], Christy et al. [14], and more recently by the Ghent group that has employed Regge theory to describe this transition region.

This then is where low Q^2 non-resonant meson production in the SIS region transitions into higher Q^2 quark-fragmented meson production in the DIS region. The need of improved understanding of $\nu_l/\bar{\nu}_l$-nucleus scattering cross sections in this transition region has generated considerable interest in studying Quark-Hadron Duality (duality) in the weak sector.

Duality has been studied in the electroproduction sector for both nucleon and nuclear targets and there is a body of evidence that duality does approximately hold in this sector. The few studies of duality in the weak sector have had to be based on theoretical models since no high-statistics, precise experimental data is available. These studies have not been encouraging suggesting that increased experiment and better modeling is required and suggests caution in using the approach of simply extrapolating the DIS cross sections to lower hadronic mass W used in some MC generators to estimate non-resonant π as well as resonant multi-π production in the weak sector SIS region.

1.2 Deep-Inelastic Scattering

Increasing W and Q^2 of the interaction brings the regime of deep-inelastic scattering. The definition of DIS is based upon the kinematics of the interaction products and is primarily defined with $Q^2 \geq 1.0$ GeV^2. To further separate resonance produced pions from quark-fragmented pions a requirement of $W \geq 2.0$ GeV is made. In the DIS region, charged lepton induced processes have been used to explore quark and gluon structures of nucleons and nuclei for quite some time. Early in the study it was assumed that the structure functions of a free nucleon would be the same as the structure functions of a nucleon within the nucleus environment. However, close to four decades ago EMC performed experiments using a muon beam in the energy region of 120-280 GeV and measured cross sections from an iron target compared with the results on a deuterium target. It was found that the ratio of the cross section $\frac{2\sigma_{Fe}}{A\sigma_D}$ is not unity in the DIS region. This was surprising as this is the region where the underlying degrees of freedom should be quarks and gluons, while the deviation from unity suggested that nuclear medium effects were important.

In these ($\ell^{\pm}$-A) DIS interactions the deviation from 1.0 in the ratio of nuclear to nucleon structure functions as a function of $x_{Bjorken}$ ($\equiv x$), reflecting these nuclear medium effects, have been categorized in four regions: "shadowing" at lowest-x ($\lessapprox 0.1$), "antishadowing" at intermediate x (0.1 to $\lessapprox 0.25$), the "EMC effect" at medium x (0.25 to $\lessapprox 0.7$) and "Fermi Motion effect" at high x ($\gtrapprox 0.7$). Various attempts have been made both phenomenologically as well as theoretically to understand these nuclear medium effects. However, while the shadowing and Fermi motion regions are now better understood, there is still no community-wide, accepted explanation for antishadowing and the EMC effect.

In the study of DIS, neutrinos have significant importance over charged-leptons by having an ability to interact with particular quark flavors which help to understand the parton distributions inside the target nucleon. Hence, precise determination of weak structure functions ($F_{iA}^{WI}(x, Q^2)$; $i = 1, 2, 3, L$) is important. The nuclear effects in neutrino DIS analyses had been assumed to be the same as for charged lepton-nucleus ($\ell^{\pm}$-A) DIS data. However there are now both theoretical and experimental suggestions that the nuclear effects in the DIS region may be different for $\nu_l/\bar{\nu}_l$-nucleus interactions as there are contributions from the axial current in the weak sector and different valence and sea quark contributions for each observable. Therefore, an independent and quantitative understanding of the DIS nuclear medium effects in the weak sector is required.

The historical experimental study of neutrino-nucleus (ν-A) scattering in the DIS region is summarized in [16] and began during the bubble chamber era of the 1970's It continued through the higher-statistics, mainly iron and lead experiments, of the 1990's using higher energy $\nu/\bar{\nu}$ beams Currently MINERνA at Fermilab is dedicated to the measurement of these cross section to better understand the nuclear medium effects and has taken data using the medium energy NuMI beam ($< E_\nu >\sim 6$ GeV) in ν_l as well as $\bar{\nu}_l$ modes with several nuclear targets ^{12}C, ^{56}Fe and ^{208}Pb and the large central scintillator (CH) tracker. In addition to the dedicated MINERνA experiment there are the T2K experiment in Japan as well as the NOvA experiment in the USA, although primarily oscillation experiments, also currently contributing to cross section measurements. At these lower energies, SIS events dominate however DIS events still contribute to the event rates although with more limited kinematic reach.

1.3 Monte Carlo Event Generators

The method for testing the relevant nuclear models with experimental results involve the Monte Carlo (MC) generator the experiments employ. At present several MC generators have been developed like GiBUU [3], NuWro [17], GENIE [18] and NEUT [19] that are used within the experimental community. These MC generators each have variations of a nuclear model, plus many other experiment dependent effects that are usually more accurately determined, involved in predicting what a particular experiment should detect. Comparing the predictions of these generators with the experimental measurements gives an indication of the accuracy of the nuclear model employed.

In addition to refining the nuclear model, the MC generator is also a necessary component for determining important experimental parameters such as acceptance, efficiency and systematic errors. To perform all these functions the MC generators need production models for each of the interactions they simulate as well as the nuclear model. For resonance production the (often modified) Rein-Sehgal model [20] (R-S) or the more recent Berger-Sehgal (B-S) model [21] is widely used. However these models mainly cover single pion production. It is essential to also study the full multi-pion production from the various nucleon resonances in the energy region of 1 - 10 GeV. For most MC generators the DIS process is simulated using the Bodek-Yang model [10]. This DIS simulation is then extrapolated down into the SIS region. The extrapolation is then weighted to avoid double counting resonance production and is then supposed to account for all non-resonant processes and missing resonant multi-π production.

It is interesting to note that there is a common thread among MC event generators in attempts to bridge the transition from the SIS to DIS regions. As a practical procedure for addressing this SIS region in contemporary neutrino event generators, such as GENIE, Bodek and Yang [22] introduced a model (BY) that is used to bridge the kinematic region between the Delta resonance and DIS. This BY model is also used by GENIE and other event generators to describe the DIS region as well. The model was developed using results from *electron-nucleon* inelastic scattering cross sections. The model incorporates the GRV98 [23] LO parton distribution functions replacing the variable x with their ξ_w scaling variable to include the effects of dynamic higher twist effects through a modified target mass correction. These modified parton distribution functions are used to describe data at high Q^2 and down to 0.8 GeV^2. Below Q^2 = 0.8 GeV^2 they take the GRV98 LO PDFs to get the value of $F_2(x, 0.8\, GeV^2)$ and multiply it by quark-flavor dependent K factors to reach lower Q^2 and W.

At the planned accelerator-based, long-baseline ν_l-oscillation experiments such as the Deep Underground Neutrino Experiment(DUNE) using an argon target it is expected that more than 30% of the events would come from the DIS region and around 50% of the events would come from the SIS(W $\geq M_\Delta$) plus DIS regions. Additionally the atmospheric ν_l studies in the proposed Hyper-K experiment (Hyper-Kamiokande), using water target, will also have significant SIS and DIS contributions. It is consequently important to have improved knowledge of nuclear medium effects in these lower-energy regions and therefore quite necessary to revisit the present status of both the theoretical/phenomenological and experimental understanding of these scattering processes.

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