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Surprising Results for Nuclear Effects in Neutrino-Nucleus Interactions and the MINERνA Neutrino Nucleus Scattering Program

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Nuclear effects of charged current deep inelastic neutrino-iron scattering have been studied in the frame-work of a χ^2 analysis of parton distribution functions (PDFs). A set of iron PDFs have been extracted which are then used to compute x_{Bj}-dependent and Q^2-dependent nuclear correction factors for iron structure functions which are required in global analyses of free nucleon PDFs. Upon comparing our results with nuclear correction factors from neutrino-nucleus scattering models and correction factors for $\ell^{\pm}$-iron scattering we find that, except for very high x_{Bj}, our correction factors differ in both shape and magnitude from the correction factors of the models and charged-lepton scattering. The MINERνA neutrino-nucleus scattering experiment at Fermilab, will systematically study neutrino nuclear effects off of He, C, Fe and Pb for a more thorough A-dependent study of nuclear PDFs and these correction factors.

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1. Nuclear Parton Distribution Functions

The high statistics measurements of neutrino deeply inelastic scattering (DIS) is of significant interest since these measurements could provide valuable information for global fits of parton distribution functions (PDFs). To acquire significant statistics, the use of heavy nuclear targets is unavoidable due to the weak nature of the neutrino interactions. This complicates the extraction of free nucleon PDFs because corrections must be applied to the data to convert from the nucleus A to a nucleon. In most PDF analyses, the nuclear correction factors were taken from $\ell^{\pm}$-nucleus scattering and used for both charged-lepton and neutrino scattering. In this study we reexamine the source and size of the nuclear corrections that enter the PDF global analysis for neutrino-nucleus scattering.

A recent study [1] analyzed the impact of new data sets from the NuTeV [3], CHORUS, and E-866 Collaborations on the PDFs. This study found that the NuTeV data set (together with the model then used for the nuclear corrections) pulled against several of the other data sets, notably the E-866, BCDMS and NMC sets. Reducing the nuclear corrections at large values of x reduced the severity of this pull and resulted in improved χ^2 values. These results suggested on a purely phenomenological level that the appropriate nuclear corrections for ν-DIS may well be smaller than the assumed $\ell^{\pm}$-nucleus corrections.

To investigate this question further, the data from the high-statistics ν-DIS experiment, NuTeV, was used to perform a dedicated PDF fit to neutrino–iron data.[2] The methodology for this fit is parallel to that of the previous global analysis,[1] *but* with the difference that only Fe data has been used and no nuclear corrections have been applied to the analyzed data; hence, the resulting PDFs are for a bound proton in an iron nucleus. Specifically, the iron PDFs were determined using the recent NuTeV differential neutrino (1371 data points) and anti-neutrino (1146 data points) DIS cross section data,[3] as well as the NuTeV/CCFR dimuon data (174 points) which are sensitive to the strange quark content of the nucleon. Kinematic cuts of $Q^2 > 2$ GeV and $W > 3.5$ GeV were imposed, and a good fit with a χ^2 of 1.35 per data point was obtained.[2] The extracted iron PDFs are shown on slide 22 of the powerpoint presentation available at (Working Group S2:WG2):

http://indico.ific.uv.es/indico/conferenceOtherViews.py?view=standardconfId=71 .

2. Nuclear Correction Factors

By comparing these iron PDFs with the free-proton PDFs (appropriately scaled) a neutrino-specific heavy target nuclear correction factor R can be obtained which should be applied to relate these two quantities. In addition to kinematic variables, R can depend on the observable under consideration simply because different observables may be sensitive to different combinations of PDFs. For example, the nuclear correction factor R for F_2^A and F_3^A will, in general, be different. Additionally, the nuclear correction factor for F_2^A will yield different results for the charged current ν–*Fe* process ($W^{\pm}$ exchange) as compared with the neutral current $\ell^{\pm}$–*Fe* process (γ exchange). Since the iron PDFs are extracted from only iron data, no particular form for the nuclear A-dependence is assumed; hence the extracted R ratio is essentially model independent.

We also observe that the neutrino and anti-neutrino results coincide in the region of large x where the valence PDFs are dominant, but differ by a few percent at small x due to the differing strange and charm distributions.

The nuclear correction factors for $F_2^{\nu Fe}$ and $F_2^{\bar{\nu} Fe}$ at Q^2 = 5 GeV^2 and 20 GeV^2 derived in this analysis and labeled A2 are shown on slides 23 -26 of the powerpoint presentation previously referenced.

The SLAC/NMC curve in the figures has been obtained from an A and Q^2-independent parameterization of calcium and iron charged–lepton DIS data.[1] The curves labeled "KP" are from the Kulagin-Petti model .[4] constructed specifically to compute the nuclear effects in neutrino-nucleus interactions. Due to the neutron excess in iron, both the A2 and the KP curves differ when comparing scattering for neutrinos and anti-neutrinos.

Although the results of this analysis have general features in common with the KP model and the SLAC/NMC parameterization, the magnitude of the effects and the x-region where they apply are quite different. The present results are noticeably flatter than the KP and SLAC/NMC curves, especially at moderate-x where the differences are significant. The general trend we see when examining these nuclear correction factors is that the anti-shadowing region is shifted to smaller x values, and any turn-over at low x is minimal given the PDF uncertainties. More specifically, there is no indication of "shadowing" in the NuTeV neutrino results. In general, these plots suggest that the size of the nuclear corrections extracted from the NuTeV data are smaller than those obtained from charged lepton scattering (SLAC/NMC) or from the set of data used in the KP model.

3. The MINERνA Experiment at the FNAL Main Injector Neutrino Beam (NuMI)

The NuMI Facility at Fermilab, based on the 120 GeV protons from the Main Injector (MI) accelerator, is providing an extremely intense beam of neutrinos for the MINOS Neutrino Oscillation Experiment, yielding several orders of magnitude more events per kg of detector per unit of time than the earlier Tevatron neutrino beam. It is an ideal place for a high statistics (anti)neutrino-nucleon/nucleus scattering experiments. The MINERνA (Main Injector ExpeRiment: ν A) experiment, a collaboration of elementary-particle and nuclear physicists, is installing a fully active fine-grained solid scintillator detector in this NuMI beam. The overall goals of the experiment are to measure absolute exclusive cross-sections, study nuclear effects in ν - A interactions (with A varying from He to Pb), perform a systematic study of the resonance-DIS transition region and the lower Q^2 DIS region including the extraction of high-x$_{Bj}$ parton distribution functions.

3.1 The MINERνA Detector

The MINERνA detector is a hybrid of a fully-active fine-grained detector and a traditional calorimeter and is made up of a number of sub-detectors with distinct functions in reconstructing neutrino interactions. The fiducial volume for most analyses is the inner “Active Target” where all the material of the detector is the scintillator strips themselves. The scintillator detector does not fully contain events due to its low density and low Z, and therefore, the MINERνA design surrounds the scintillator fiducial volume with sampling detectors. To construct these sampling detectors, the scintillator strips are intermixed with absorbers. For example, the side and downstream (DS) electromagnetic calorimeters (ECALs) have lead foil absorbers. Surrounding the ECALs are the hadronic calorimeter (HCAL) where the absorbers are steel plates. On the sides of the detector the outer detector (OD) plays the role of the HCAL. In the upstream end of the detector are the nuclear targets of pure C, Fe and Pb as well as a LHe target. The He target vessel is directly upstream of the main MINERνA detector. Upstream of the detector and LHe target vessel is a veto of steel and scintillator strips to shield MINERνA from incoming soft particles produced upstream in the hall. A complete description of MINERνA is found in the proposal [6] and TDR [7].

For this report the emphasis is on the nuclear targets. In the standard 4-year run for MINERνA the statistics will range from 400k events on He and pure carbon to 2M events on iron, 2.5M events on lead and 8.6M events on scintillator (CH). These targets are exposed simultaneously to the same beam which means that beam-associated systematic errors essentially divide out and only detector-associated systematics enter the errors on the ratios of targets. This will allow a very accurate determination of the R factors over a wide range of x and Q^2

4. Conclusions

The detailed x and Q^2 behavior is quite different when comparing the nuclear corrections extracted from ν–Fe scattering compared to $l^{\pm}$–Fe charged-lepton results. There is no *a priori* reason to expect them to be the same. On the contrary, with the introduction of the axial-vector current in neutrino scattering, it would be difficult to understand if they were exactly the same. What was unexpected was the degree to which the R factors differ between ν–Fe scattering compared to $l^{\pm}$–Fe charged-lepton results. In particular the lack of evidence for shadowing in neutrino scattering, confirmed by Sergey Kulagin [8] for CHORUS and NOMAD data, is quite surprising.

The nuclear correction factors R will be measured over a wider range of A and with reduced errors by the MINERνA experiment in the NuMI beam in the near future.

References

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