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MINERvA measurement of neutrino charged-current cross section ratios of nuclei C, Fe, and Pb to CH at energies of a few GeV

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Abstract

The MINERvA experiment is designed to measure neutrino cross sections for different nuclei using substantially similar fiducial and tracking environments. This allows for reduced systematics in the ratio to better see the evolution of the cross section with the size of the nucleus. The first such result is an inclusive charged current cross section ratio as a function of energy from and the kinematic quantity Bjorken x for nuclei Pb, Fe, and C relative to plastic scintillator CH. The measurement is made for neutrino energies from 2 to 20 GeV. In the past, charged lepton scattering ratios of heavier nuclei to deuterium have revealed interesting structure such as the EMC effect. These ratios were restricted to purely deep inelastic scattering data whereas these ratios to different nuclei in MINERvA are sensitive to the elastic scattering as well as resonance production regions. Significant deviations from the baseline scattering model are observed, and suggest new theory work to investigate these ratios.

Keywords:

1. Introduction

The goal of the MINERvA physics program is to make world leading measurements of neutrino cross sections. In addition to cross sections on CH (active detector plastic scintillator), the experiment has passive targets of Pb, Fe, C (Graphite), H_2O, and He. These targets hang between standard MINERvA tracking layers and are upstream of the main tracking region. This configuration is designed for the analysis of the ratio of the event rate in these targets to the event rate in the main tracking region. Taking data in the same beam with nearly the same tracking environment allows many kinds of experimental uncertainties to cancel in the ratio. The results in these proceedings are published [1] and contain more details, discussion, and tables of the cross section results and systematics.

Charged electron and muon scattering experiments have long produced measurements of such ratios for deeply inelastic scattering (DIS) scattering off different nuclei, starting with the original publication of results from the European Muon Collaboration (EMC) [2, 3]. These and later results for nuclei relative to deuterium show ∼20% deviations from unity for structure functions. From low to high values of the Bjorken x scaling variable $x_{bj} = Q^2/2M\nu$ these deviations are colloquially described as the shadowing, anti-shadowing, and EMC effect regions. In the MINERvA case, quasi-elastic nucleon process details such as Fermi motion dominate near x = 1. Even with these data, the origin of the latter effect is not fully explained in terms of nuclear or parton structure. Among more recent work on interpretation, the analyses of [4, 5, 6] find an interesting correlation between the magnitude of the x_{bj} EMC effect in nuclei and the probability to find short range correlated pairs of nuclei for quasi-elastic scattering in the nucleus.

MINERvA's ability to provide cross section ratios gives access to the evolution of the axial component of the structure functions xF_3, F_2 for DIS as well as the quasi-elastic and resonance production. Beyond probing the fundamental nature of nuclear structure, these measurements directly provide information to predict neutrino nucleus event rates on the full range of nuclei for current and upcoming neutrino oscillation experiments. Though only three nuclei are tested with these first results, MINERvA has data on H_2O and Helium, and the success of these first measurements could be a precursor to making the similar ratio measurements with Argon.

2. Experiment and sample

The MINERvA experiment [7] is a large, fine-grained tracking detector with a central region made of active plastic scintillator tracking layers and a passive nuclear target region in front. It is surrounded by calorimetry layers and uses the MINOS Near Detector [8] as a downstream muon spectrometer. The experiment is located at Fermilab in the NuMI neutrino beam. These results are from the 2010 to 2012 operation of that beam in neutrino focused mode during the so-called Low Energy configuration which has a flux such that the event rate peaks at 3.5 GeV with a long high energy tail. This analysis is restricted to neutrino energies $2 < E_\nu < 20$ GeV, and to ensure acceptance uniformity when requiring the muon's momentum be measured downstream, a restriction that $\theta_\mu < 17°$ is imposed on the sample.

The four passive planes of target nuclei considered for this analysis have tracking layers between each of them. One plane is split between 1" thick Pb and Fe, one is split three ways between 1" thick Pb and Fe with 3" thick graphite, another is 0.3" Pb, and the final one is 0.5" Fe and Pb. Interactions in the main tracking region of the MINERvA detector are selected in such a way that the CH samples used for each nucleus/CH ratio follow a similar geometrical pattern and are statistically independent from the other samples.

When a neutrino interaction event is identified and a reconstructed muon is measured downstream, the tracking information is used to identify the location of the interaction point. The event selection avoids the transverse boundary region between passive materials, so backgrounds from the "wrong" nuclei are minimal. Backgrounds from the CH tracking layers adjacent to each passive target are substantial; these backgrounds are estimated using data in the fully active tracking region and subtracted.

The hadronic system is reconstructed from the calorimetric sum of all activity in the event not associated with the muon. After accounting for the passive material, the full correction to the estimated energy transfer from the lepton to the hadron system $\nu = E_\nu - E_\mu \approx E_{\mathrm{had}}$ requires a model-based correction which is made using the full MC to account for missing energy from neutral particles and the unbinding of nucleons. The single hadron response uncertainties of this detector are constrained using test beam data, and other uncertainties on this quantity from the neutrino cross section and final state hadron re-interaction models play a significant role in this estimator. The neutrino energy is then the sum of the muon energy and this calorimetric hadron energy, and finally Q^2 and $x_{bj} = Q^2/2M_N\nu$ are computed in the traditional way. More detailed information on this analysis process, resolutions, and systematics are available from [1, 7].

3. Results

The cross section ratios as a function of energy are shown in Fig.1. The data are shown with statistical uncertainties, which is the largest source of uncertainty for these results. The simulation shows the uncertainties coming into the background subtraction, detector response, and aspects of the cross section model that affect the unfolding and acceptance correction. Because this is a ratio of data taken simultaneously in the same beam, uncertainties in the flux are negligible. The simulation is based on the GENIE (version 2.6.2) neutrino event generator [9], and includes adjustments from [10] that describe the effects of DIS scattering on Fe relative to D, as an approximation. The comparisons are to CH; predicted deviations from consistency are not expected to be large as they would be for ratios to pure hydrogen or deuterium. Since this is a cross section on specific nuclei, and not an isospin corrected structure function, deviations from unity for heavier, neutron rich nuclei are expected. The results as a function of energy are consistent with the prediction from the model.

In contrast to the good agreement for $\sigma(E)$ ratios, the cross section ratios as a function of x_{bj} in Fig. 2 show a dramatic trend in the elastic region at and above $x_{bj} = 1$. These plots' horizontal axis is the reconstructed quantity and no unfolding is performed. The average energy of the sample is 8 GeV, the beam produces an event rate that peaks at 3.5 GeV, and the sample is inclusive. Unlike traditional DIS analyses at higher energies and Q^2, this makes this sample especially high in quasi-elastic and resonance production events. For this kind of hadronic system, fluctuations around low multiplicity hadron final states create a resolution in x_{bj} that can not be unfolded using standard techniques.

To describe the same problem a different way, there is a large predicted migration from higher statistics mod-

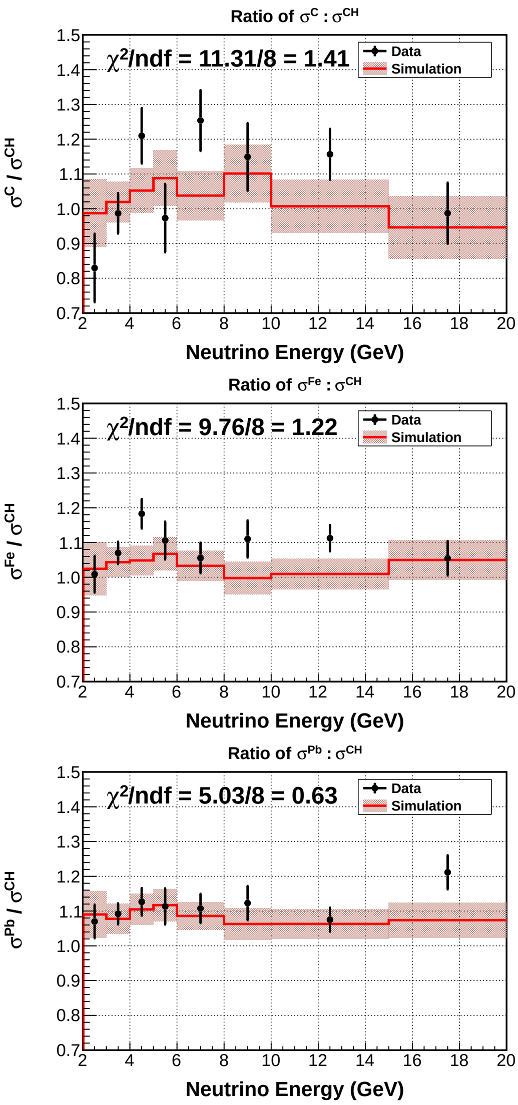

Figure 1: The cross section ratios as a function of neutrino energy. These results use an iterative unfolding technique to account for resolution effects.

erate x_{bj} to lower statistics high x_{bj}. At this time, it is not clear whether the discrepancy is better explained as a discrepancy in the quasi-elastic and resonance cross sections which are likely to be reconstructed at $x_{bj} \geq 1$ or more generally with nuclear effects that play a role in how far and how likely is event migration to higher reconstructed x_{bj}. The mean value of Q^2 for the high reconstructed x_{bj} data is $Q^2 \approx 1.0$ GeV^2 combined with low reconstructed E_{had}.

The nuclear environment simulated by GENIE [9] for events in the elastic-like region is a Fermi-gas model, contains only QE and resonance interactions, but no multi-nucleon effects such as 2p2h processes or detailed nucleon-nucleon correlations. Some predictions of these effects do not yield strong dependence of the cross section with size A of the nucleus, for example [11], though the effects on a quantity like x_{bj} has not been fully explored. As noted in the introduction, it has been suggested short range correlations in the electron scattering quasi-elastic process and the EMC effect in charged lepton DIS scattering may have a common cause. In addition to not predicting the reconstructed x_{bj} distribution, the default GENIE model does not do an adequate job describing neutrino-CH interactions, as discussed in three other MINERvA results [12, 13, 14].

Another feature the simulation has trouble modeling is a relative depletion of events at low x_{bj} for heavy nuclei is compared to light nuclei. This is the highest statistics part of the sample, and also the closest to a traditional DIS sample, though at relatively low $< Q^2 >= 0.23$ GeV^2. This data point is predicted by the model to have a large ~40% component from resonance interactions.

4. Discussion

Having different target nuclei in the same experiment has produced a important data set [1]. MINERvA expects to make use of a new higher energy data set which brings with it more substantial DIS content and more statistics, and to look at cross section ratios for quasi-elastic-like events separate from highly inelastic events.

The observation of significant discrepancies, both in the high statistics low x_{bj} region as well as the quasi-elastic-like high x_{bj} region has repercussions for neutrino oscillation experiments searching for mass hierarchy and CP violation effects. Most will operate at energies where the latter are especially important and some depend on the unique kinematics of the quasi-elastic process for forming the neutrino energy spectrum. A particular favorite nucleus is argon-40, which happens to have a size A similar to Fe, but a neutron excess more similar to Pb, making extrapolation of these discrepancies challenging. The full exploitation of the MINERvA data set, as well as new dedicated cross section measurements on argon will be important to proposed neutrino oscillation physics programs.

In summary, MINERvA has provided first results for charged current cross section ratios among different nuclei. These first results for the inclusive process are dominated by statistics, partly because the mass of the targets is modest and partly because major systematics have reduced effect on the ratio. The flux uncertainty is

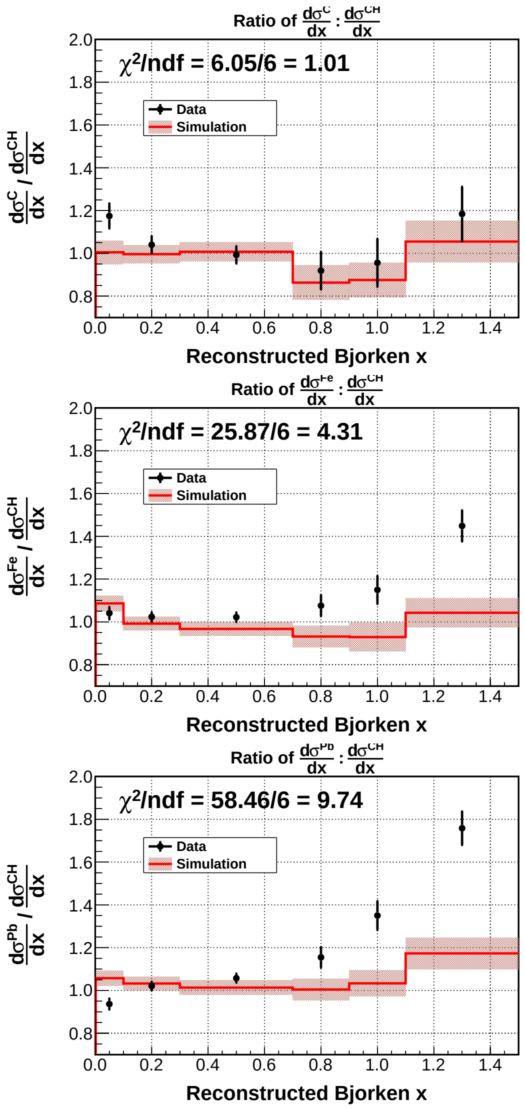

Figure 2: The cross section ratios as a function of reconstructed x_{bj}. These comparisons with the model are presented as the resolution smeared reconstructed variable.

a particularly small contribution. The results for $\sigma(E)$ are well described by the model, but results for $d\sigma/dx_{bj}$ ratios show significant deviations from the model that evolve with the size of the nucleus.

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