Measurement of the nuclear dependence of the EMC effect at large x

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Inclusive electron scattering from nuclear targets has been measured to extract the nuclear dependence of structure function F_2^A in Hall C at the Thomas Jefferson National Accelerator facility. Results are presented for ^{2}H, ^{3}He, ^{4}He, ^{9}B, ^{12}C, ^{63}Cu and ^{197}Au at incident electron beam energy of 5.77 GeV for a range of momentum transfers from Q^2=2 to 7 (GeV/c)^2. These data improve the precision of the existing measurements of the EMC effect in the nuclear targets at large x, and allow for more detailed examinations of the A dependence of the EMC effect.

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I. INTRODUCTION

Quantum chromodynamics (QCD) is the theory governing the strong interaction, with quarks and gluons as elementary degrees of freedom. The interaction between quarks is mediated by gluons as the gauge bosons. Understanding QCD in terms of the elementary quark and gluon degrees of freedom remains the greatest unsolved problem of strong interaction physics. The challenge arises from the fact that quarks and gluons cannot be examined in isolation. The degrees of freedom observed in nature (hadrons and nuclei) are different from the ones typically used in the QCD formalism (quarks and gluons). However, detailed studies of the structure of hadrons, mainly protons and neutrons, provide a wealth of information on the nature of QCD. Thus, one of the main goals of the strong interaction physics is to understand how the fundamental quark and gluon degree of freedom give rise to the nucleons and to inter-nucleon forces that bind nuclei.

The investigation of deep-inelastic scattering of leptons off the nucleon is one of the most effective ways for obtaining fundamental information on the quark-gluon substructure of the nucleon. Nuclear structure functions probe the impact of the nucleon binding and motion in the nucleus, as well as possible modification to the structure of a nucleon in the nuclear medium. Measurements by the European Muon Collaboration [1] showed the unexpected result that the nuclear structure function differed significantly from the sum of proton and neutron distributions. This observation was dubbed the 'EMC

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effect', and is still the focus of experimental and theoretical efforts to understand the origin of these differences in detail. We decribe here an experiment where electrons were scattered off from proton and several other nuclear targets to better understand the possible modification of hadron properties in the nuclear environment, with a focus on light nuclear targets.

This article is structured as follows. In the next section we briefly discuss electron scattering, structure functions and introduce the kinematics. In section I we discuss the EMC effect and do a short survey of the findings of earlier experimental and theoretical investigations and briefly discuss the physics motivation behind the present experiment. Section II gives an overview of the experimental apparatus used to collect the presented data. Section III describes the data analysis procedures and section IV discusses the details of the systematic uncertainties. The final results are presented in section V with conclusions and an overview of the results given in section VI.

A. Kinematics and definitions

Consider electron scattering off a stationary target nucleon through the exchange of a single virtual photon,

$$e^{-}(k) + N(P) \longrightarrow e^{-}(k^{'}) + X \ , \tag{1}$$

where k and $k^{'}$ are the four momenta of the initial and scattered electrons and P is the four momentum of the target nucleon. The four momentum of the incoming electron is $k = (E, \overrightarrow{k})$ and of the scattered electron is $k = (E^{'}, \overrightarrow{k})$. Since the target is at rest in the laboratory frame its four momentum is $P = (M, \overrightarrow{0})$ where M is the nucleon rest mass. Experimentally, the produced hadrons X are not detected in inclusive scattering of electrons with a fixed energy, E. Only the scattered electron energy $E^{'}$ and the scattering angle θ relative to the incident beam. The scattering process takes place through the electromagnetic interaction by the exchange of a virtual photon γ^{*}, with energy, $\nu = E - E^{'}$ and momentum $\overrightarrow{q}$. In the laboratory frame and ignoring the electron mass, one can express the negative of four momentum transfer square of the virtual photon exchanged in the scattering process as $Q^2 = 4EE^{'}\sin^2(\theta/2)$ and the invariant mass of the final hadronic system as $W = \sqrt{M^2 + 2M\nu - Q^2}$. The Bjorken scaling variable, $x = Q^2/2M\nu$, represents the longitudinal momentum fraction of the hadron carried by the interacting parton in the infinite momentum frame. For electron scattering from a free nucleon, x ranges from 0 to 1. For scattering from a nucleus of mass number A, the x range goes from 0 to $M_A/M \approx A$.

In terms of the deep-inelastic structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$, the differential cross section for scattering of an unpolarized electron in the laboratory frame can be written as

$$\begin{aligned} \frac{d^2\sigma}{d\Omega dE^{'}} &= \frac{4\alpha^2 E^{'2}}{Q^4}\cos^2(\theta/2)\big[F_2(x,Q^2)/\nu \\ &\quad + 2\tan^2(\theta/2)F_1(x,Q^2)/M\big] \ , \end{aligned} \tag{2}$$

where α is the fine structure constant. For brevity, this doubly differential cross section is denoted by the symbol σ. When Q^2 and $\nu \to \infty$, the structure functions will only depend on the ratio Q^2/ν or equivalently on the variable x [2]. Thus, in this scaling region the structure functions are simply a function x. In the quark parton model (QPM), this scaling behavior is due to the elastic scattering of the quarks inside the nucleon. In this model, the structure function F_2 is given by

$$F_2(x) = \sum_f e_f^2 x q_f(x) \ . \tag{3}$$

where the distribution function $q_f(x)$ is the expectation value of the number of partons of flavor f (up, down, strange...) in the hadron, whose longitudinal momentum fraction lies within the interval $[x, x+dx]$ and e_f is the charge of the parton, in units of electron charge.

Experimentally this scaling is not exact. In the region of deep-inelastic scattering (DIS), the structure functions do not scale exactly, and instead depend logarithmically on Q^2. This is a consequence of QCD, in which the parton distribution functions (pdfs) are not scale independent, but evolve with Q^2. So the logarithmic scaling violations associated with QCD do not break down the connection between the structure function and the underlying pdfs, but simply reflect the scale-dependence of the pdfs.

Along with the Q^2 dependence associated with QCD, additional power corrections appear at lower Q^2 values, mainly at large x. So-called "target mass corrections" [3] yield deviations from scaling at finite Q^2 values arising from terms neglected in the high-Q^2 approximations used in the ideal scaling limit. In addition, higher-twist effects, associated with breakdown of the assumption of incoherent elastic scattering from individual quarks at lower Q^2, also modify the scaling behavior. This is most clearly manifested in the appearance of clear structures in the inclusive structure function associated with production of individual resonances.

Analogous to the absorption cross section for real photons, the F_1 and F_2 structure functions can be expressed in terms of longitudinal (σ_L) and transverse (σ_T) virtual-photon cross sections

$$\frac{d^2\sigma}{d\Omega dE^{'}} = \Gamma\left[\sigma_T\left(x, Q^2\right) + \epsilon\, \sigma_L\left(x, Q^2\right)\right] \ , \tag{4}$$

where $\epsilon = \Gamma_L/\Gamma_T = \left[1 + 2\,(1 + Q^2/4M^2x^2)\tan^2\frac{\theta}{2}\right]^{-1}$ is the virtual polarization parameter, Γ is the virtual photon flux, and Γ_L and Γ_T defines the probability that a lepton emits a longitudinally or transversely polarized virtual photon.

The ratio of longitudinal to transverse virtual-photon absorption cross section is given by

$$R(x,Q^2) = \frac{\sigma_L}{\sigma_T} = \left[\left(1+\frac{\nu^2}{Q^2}\right)\frac{M}{\nu}\frac{F_2(x,Q^2)}{F_1(x,Q^2)}\right] - 1 \ . \quad (5)$$

Using equations 2 and 5, the per-nucleon cross section (cross section divided by the total nucleon number) ratios for two different nuclei A_1 and A_2 can be written as

$$\frac{\sigma_{A_1}}{\sigma_{A_2}} = \frac{F_2^{A_1}\,(1+\epsilon\, R_{A_1})\,(1+R_{A_2})}{F_2^{A_2}\,(1+\epsilon\, R_{A_2})\,(1+R_{A_1})} \ . \quad (6)$$

Note that when $\epsilon = 1$ or $R_{A_1} = R_{A_2}$, the ratio of the F_2 structure functions is identical to the cross section ratio.

In this and all previous extractions of the EMC effect, it is assumed that R is target independent, and therefore the cross section ratios correspond to the F_2 structure function ratios. Because the structure functions depend on Q^2, this ratio may also have a Q^2 dependence which we must account for in comparing our data to measurements at other different Q^2 values. However, the effect of QCD evolution on the ratios should be essentially negligible as the evolution is nearly identical for all nuclei, and so cancels in the ratio. The only significant contribution to the ratio from target mass corrections corresponds to a simple change of variables from Bjorken-x to Nachtmann-ξ when comparing measurements at different Q^2 (Sec. III K). Thus, in kinematics where any remaining higher-twist contributions are small or A independent, the comparison of EMC ratios from experiments at different Q^2 values is straightforward. Accounting for this change of variables mentioned above, it has been shown that the EMC ratios are independent of Q^2 down to very low values of Q^2 and W^2, well below the typically-defined DIS regime [4, 5].

B. EMC effect

Nuclei consist of protons and neutrons bound together by the strong nuclear force, with binding energies of 1–2% of the nucleon mass, and characteristic momenta below 200–300 MeV/c. Because DIS involves incoherent scattering from the quarks, and the energy and momentum scales associated with nuclear binding are small compared to the external scales in DIS, the naive assumption was that the nuclear structure function in high-energy scattering from a nucleus with Z protons and N neutrons would simply be the sum of the proton and neutron structure functions:

$$F_2^A(x,Q^2) = ZF_2^p(x,Q^2) + NF_2^n(x,Q^2) \ . \quad (7)$$

While the typical scale of the Fermi momentum is small compared to the momentum scale of the probe, the longitudinal component is directly added to the momentum of the virtual photon and cannot be completely neglected. It is necessary to perform a convolution of the pdfs of the proton and neutron with the momentum distribution of the nucleons in the nucleus [6]:

$$F_2^A(x) = \int_x^A dz\, f_N^A(z,\epsilon) F_2^N\left(\frac{x}{z}\right) \ , \quad (8)$$

where the longitudinal momentum distribution function $f_N^A(z,\epsilon)$ for the nucleon is given by,

$$f_N^A(z,\epsilon) = \int d^4p\; S_N(p)\; \delta\left(z - \left(\frac{pq}{M_N q_0}\right)\right) \ . \quad (9)$$

Here, $S_N(p)$ is the spectral function of the nucleus (here assumed to be identical for protons and neutrons), z is the light-cone momentum carried by the nucleon and ϵ its removal energy. The four-momenta of the struck nucleon and virtual photon are given by p and q, where q_0 is the energy transferred by the virtual photon. One can think of the convolution as "smearing" the nucleon pdf in x, yielding little change where the pdf is relatively flat in x, and larger effects where it grows or falls rapidly. Calculations showed that the effect was minimal at low x values, but that the convolution has a large impact for $x \gtrsim 0.6$, where the pdf of the nucleon falls rapidly [7–9].

Therefore, it came as a surprise when this expectation was shown to be incorrect by measurements which showed significant effects on the nuclear pdf for nearly all values of x [1]. As part of a comprehensive study of muon scattering, the European Muon Collaboration compared data from iron with data from deuterium by forming a per-nucleon structure function ratio of these targets. Since the x distributions of up and down quarks differ, yielding different structure functions for the proton and neutron, EMC ratios are usually taken as a ratio of a heavy isoscalar target to deuterium. This cancels out the contribution due to the difference between the proton and neutron structure function but yields a ratio which depends on the nuclear effects in both the heavy nucleus and the deuteron. For non-isoscalar nuclei, a correction is typically applied to estimate the effect of the neutron excess in heavy nuclei. Note that many calculations provide the ratio of the heavy nucleus to the sum of free proton and neutron structure functions. This provides a more direct measure of the nuclear effects in the nucleus, but cannot directly be compared to the data, as the lack of a free neutron target makes direct measurements of the free neutron structure function impossible.

When plotted as a function of x, the EMC ratio shows significant deviation from unity. The deviation of this ratio from unity was unexpected, and, this target-mass number dependence in deep-inelastic scattering is known as the EMC effect. This discovery had a significant impact on our views of the structure of nuclei, and has spurred discussion of the importance of the concepts of quarks, gluons and QCD to nuclear physics.

Though the boundaries are somewhat arbitrary, generally the x dependence of the cross section ratios are divided into four regions in x. The gross features of the data are; the region $x < 0.1$, where the nuclear cross sections are suppressed (known as the shadowing region);

the region $0.1 < x < 0.3$, where the nuclear cross sections are slightly enhanced compared to nucleon cross sections (anti-shadowing region); the region $0.3 < x < 0.7$, where a large suppression of the nuclear cross section is observed ("EMC effect" region), and the region $x > 0.7$ where the EMC ratio increases and grows beyond unity due to the convolution ("Fermi smearing") effects.

C. Previous measurements of the EMC effect

After the initial observation of an unexpected nuclear dependence in the structure functions of heavy nuclei [1], measurements were performed at both CERN [10–12] and SLAC [13–16]. Further measurements by the EMC collaboration [17] and New Muon Collaboration () [18, 19] significantly improved the precision and kinematic range of measurements at low x, mapping out in detail the shadowing region for a range of nuclei. The HERMES collaboration also measured DIS cross sections on several nuclear targets including ^{3}He [20, 21]. The data in the anti-shadowing region are consistent with unity, while data at higher x have large uncertainties.

Focusing on the high-x region, SLAC experiment E139 [16] mapped out the EMC effect for ^{4}He, Be, C, Al, Ca, Fe, Ag, and Au in the range $0.09 < x < 0.9$ and $2 < Q^2 < 15$ GeV^2. Examining the target ratios, and in particular their deviations from unity, the experiment showed no significant Q^2 dependence and an identical x dependence for all nuclei, although the high-x behavior of ^{4}He appeared to differ, but not in a significant fashion given its large uncertainties. The A-dependence of the nuclear effects could be parameterized several different ways: varying logrithmically with A, linearly with A$^{-1/3}$, or being proportional to the average nuclear density (assuming a uniform sphere based on the measured nuclear charge radius). It common to assume that the EMC effect scales as A$^{-1/3}$ [22], based on the local density approximation [23], and this has been used to provide an extrapolation of the EMC effect to infinite nuclear matter [24].

The universal x dependence and weak A dependence for heavy nuclei makes it difficult to evaluate models of the EMC effect [25–27]. In addition, the EMC effect at very large x values had not been well measured. The typical DIS requirement, $W^2 > 4$ GeV^2, yields extremely high Q^2 measurements for $x \gtrsim 0.8$, where the cross sections are extremely small. However, recent extraction of EMC ratios from JLab experiment E89-008 in the resonance region ($1.2 < W^2 < 3.0$ GeV^2 with Q^2 = 3–4 GeV^2) demonstrated that the nuclear effects in the resonance region and DIS region are identical [4]. This implies that relaxing the constraint on W^2 may allow for measurements at larger x values than previously accessed. Precise measurements at large x allow for tests of the convolution model where other effects are expected to be small, providing a constraint on the convolution effects which must be accounted for at all x values.

D. Theoretical models

Even though it has been three decades since the discovery of the EMC effect, and there are extensive data on its x and A dependence for $A \geq 12$, there is no clear consensus as to its origin. The EMC effect has been under intense theoretical and experimental study since the original observation (see the reviews [25–27] and references therein). The formalisms used to explain the observed effect ranges from traditional nuclear descriptions in terms of pion exchange or binding energy shifts, to QCD inspired models such as dynamical rescaling, multi-quark clustering and de-confinement in nuclei, some of which involve changes to the nucleon's internal structure when in the dense nuclear medium.

Traditional calculations begin with the convolution model, where the nucleon motion and binding modify the effective x and Q^2 values of the e–N interaction, such that the virtual photon probes a modified quark distribution compared to the stationary nucleons. While the nucleus is built from several constituents, it is common to consider only the contribution from the nucleons as part of the 'conventional', and treat contributions from pions and more exotic constituents such as virtual Δs, modified nucleons, or hidden color configurations as additional contributions.

Akulinichev *et al.* [6, 28] included the mean nucleon removal energy in their calculations in addition to the simple binding and Fermi motion. They found that the experimental results can be reproduced by inclusion of the average one-nucleon separation energy, but their approach has been criticized for having incorrect normalization of the spectral function [29].

JRA: is "improper normalization of S(p)" the same as failing to satisfy the momentum sum rule?

JRA: Kulagin and Petti as more recent convolution approach (presumably better than the 1985 versions, e.g. if they do convolution for full 3D momentum distribution). Includes removal energy based on single particle separation energy, which accounts for roughly half of the observed suppression of the high-x nuclear structure function ratio. Again, this convolution yields a violation of the momentum sum rule. In their analysis, this is fixed by inclusion of an enhance pion field, although there are several assumptions that go into this.

...However, the contributions from nuclear pions are only significant at low x, as they carry a momentum fraction of m_π/m of the momentum of a nucleon in the infinite momentum frame. Thus, the structure functions for $x > 0.3$ should not be sensitive to the details of the nuclear pions (at least not directly, pion model important in their extraction of off-shell effects).

Another such calculation is by Benhar *et al.* [30]. Their binding-only contributions agrees with existing world data for the medium heavy nuclei large x values but undershoots the data at small x values. The agreement is improved when they include the contributions of "nuclear pions". Another calculation by Marco *et al.* [31]

uses realistic nucleon spectral functions and meson nucleus self energies to get the size of the EMC effect outside of shadowing region. Their calculations incorporate Fermi motion, binding, and pionic effects and uses an interacting Fermi sea and the local density approximation to scale the results from nuclear matter to finite nuclei. Here, also a better agreement with data is reached when they use both nucleonic and mesonic (pions and rhos) contributions as opposed to the nucleonic contribution alone.

JRA: The paragraph above was moved here from following section; may need to be worked in better and have more (or less?) detail.

JRA: need at least brief comment about Miller/Smith work which claims that binding can't explain the EMC effect, but in a LC convolution calculation with no binding (IIRC).

Some calculations include more than just pions and nucleons. A recent work accounts for some of the deficit in the momentum-sum rule for the nucleons by a modification to the Coulomb field of the nucleus [32, 33]. If one is starting from a convolution model which uses the separation energy, rather than the average binding energy per nucleon, accounting for the momentum in the Coulomb field simply accounts for loss of momentum from the nucleons; it does not yield an additional suppression of the structure function at large x. However, it would suggest that the modification to the nuclear pion field, used to explain the deficit of the momentum sum rule, is overestimated in heavy nuclei where the modification of the Coulomb field is more significant. These and other works, e.g. [34], also argue for the importance of accounting for the difference between x, calculated with the proton mass, and x_A calculated with the mass of the nucleus. This small shift in x will yield a suppression of the nuclear structure function at large x, and so this could be removed from the measured EMC effect. However, this effect is also accounted for in calculations of the EMC ratios which include the binding energy of the nucleus, so there is no need to apply a correction to the data for this effect when comparing to such calculations.

Additional contributions that have been examined are virtual constituents of the nucleus which are not present in a nucleon. In the dense environment of a nucleus, one may have color-singlet clusters of 6, 9,... valence quarks [35, 36]. The pdfs within such clusters can differ significantly from the sum of a set of 2 or 3 individual nucleons, just yielding a modification to the nuclear pdf. *disfavored because large contributions required to explain EMC region (?); can be examined at larger x, as multi-quark configuration the structure function extends beyond* $x = 1$ *[25, 27, 37, 38].* It has also been suggested that hidden-color configurations may contribute to the short-distance structure of the nucleus, which again could potentially yield a small contribution with a significant modification to the nucleon pdfs.

Finally, some calculations invoke a modification to the internal structure of individual nucleons within the dense medium of the nucleus. Different rescaling models [39–41] have been proposed to explain the EMC effect, based on a change in the nucleon radius due to partial deconfinement in the nuclear medium. In terms of QCD, a change in confinement means a change in Q^2. Thus, QCD evolution starts at lower Q^2 for a free nucleon, and, hence, the QCD radiative processes per nucleon are larger in a bound nucleon than in a free nucleon. In this case, scaling is referred to as "dynamic" because of the evolution of the quark, anti-quark and gluon distributions. Close *et al.* [42] shows that and increase in confinement size could explain the data on a medium nucleus such as iron but fail to explain the data for $x \gtrsim 0.65$, since there is no inclusion of Fermi motion effects.

There are other models involving medium-modified nucleons that do not use a rescaling of Q^2. In such models the quark wave function of a nucleon is modified by external fields provided by the surrounding nucleons. Quark-meson coupling models [43] include the effect of the nuclear medium by allowing quarks in nucleons to interact via meson exchange and additional vector and scalar fields. These models have been applied to the study the EMC effect in unpolarized and polarized [44, 45] structure functions, as well as other observables for nuclei and nuclear matter [46]. In addition, calculations for finite nuclei [45] show a significant difference between the polarized and unpolarized EMC effect. Recent work by Miller and Smith use a Chiral soliton model to relate nucleon form factor modification [47], the EMC effect in polarized [48] and unpolarized [49] structure functions.

The initial results from our EMC ratios on light nuclei [50] suggested that clustering effects may be important in generating the observed structure function modification [51]. One possibility suggested by this result is the idea that the local environment of the struck nucleon, rather than average nuclear density, is a driving force for much of the modification to the nuclear structure function. This does not directly explain which of the models above may yield the best microscopic explanation for the effect, but it suggests that the details of the nuclear structure may need to be incorporated into quantitative evaluations of such effect. Currently, most such calculations begin with a simple mean-field model or infinite nuclear matter, and assume a simple scaling with density or some other parameter rather than predicting the A dependence directly. As such, it has been difficult to determine which underlying physics best describes the data, as the universal x-dependence and weak A dependence of the earlier data from SLAC provided limited ability to constrain the models. With the JLab data on light nuclei, more detailed calculations need to be performed to test the A dependence associated with these models.

E. Physics motivation behind E03-103

The experiment reported here, JLab E03-103, was designed to precisely map out the x, Q^2 and A-dependence of the inclusive electron scattering from light to medium heavy nuclei, with emphasis on light nuclei and large x region [52]. Results for the EMC ratios for the light nuclei have been reported in reference [50].

While the EMC effect has been well measured in heavy nuclei, the SLAC E139 ratios for ^{4}He have large uncertainties and there are no measurements on ^{3}He in the valence region. Data on light nuclei are important in understanding the microscopic origin of the EMC effect as they allow direct comparison to detailed few-body calculations with minimal nuclear structure uncertainties. Data on light nuclei can also help constrain nuclear effects in the deuteron which are critical to the extraction of the neutron structure function from measurements on the deuteron [53–57]. The light nuclei allow for better tests of the A dependence of the EMC effect, while also providing measurements of nuclei more similar to the deuteron in mass and density.

In addition, studies of short-range correlations [58–65] suggest that high-density configurations play an important role in nuclei, which could potentially yield a modification of the nucleon structure function in overlapping nucleons [25, 27, 37, 38, 66, 67]. If two-body effects have a significant contribution to the EMC effect, then the EMC effect could look different in few-body nuclei than it does in heavy nuclei, where the effects may be saturated. There were also models which predicted a very different x dependence for the EMC effect for A=3,4 [68–71], so the inclusion of light nuclei was considered important as a way to look for two-body effects as a possible source of medium modification in nucleon structure.

Beyond the focus on light nuclei, E03-103 emphasized taking data at large x, where Fermi motion and binding effect dominate. Because of the lack of data in this region and the limited data for few-body nuclei, many calculations of the EMC effect are performed for nuclear matter and extrapolated to lower density when comparing to the nuclear parton distributions. In such cases, the important contributions of binding and Fermi motion are not modeled in detail, making it difficult to test models of effects beyond the convolution model.

While many models mentioned in the previous section have had some success, most are incomplete. They may work only in a limited x range, conflict with limitations set by other measurements, or explain the data while neglecting Fermi motion and binding. However, it is clear that the effects of binding and Fermi motion are important and contribute over the entire x region, not just at the largest x values. The large x data are particularly sensitive to these effects and to the details of nuclear structure. As such, precise high-x data for both light and heavy nuclei can help to constrain these effects.

II. EXPERIMENTAL APPARATUS

Experiment E03-103 was carried out in Hall C at the Thomas Jefferson National Accelerator Facility (JLab) [72]. The unpolarized electron beam from the Continuous Electron Beam Accelerator Facility was incident on targets. The High Momentum Spectrometer (HMS) (a magnetic focusing spectrometer) was used to detect the scattered electrons. The nominal electron beam energy (E) was measured with the Hall C arc energy measurement [?], the scattered momentum (E') and angle (θ) are reconstructed from the particle trajectory in the HMS.

A. Experiment kinematics

Most of the data for the experiment were taken at 5.776 GeV beam energy with beam currents of 30–80 μA. The cryogenic targets ^{2}H, ^{3}He,^{4}He and solid targets ^{9}B, ^{12}C, ^{63}Cu and ^{197}Au were studied. Data on all targets were taken at 40° and 50°, and the cross section ratios with respect to deuterium were extracted. At high x, the kinematics were not in the conventional DIS region ($W^2 > 4\,\mathrm{GeV}^2$), so additional data were taken for ^{12}C and ^{2}H at 8 additional kinematic settings, half at E=5.776 GeV and half at 5.01 GeV, as shown in Fig. 1.

FIG. 1: (Color online) Kinematic coverage for the experiment. Contours of constant invariant mass square are shown with black lines. Different colors represent different angles, given in the legend. Solid lines were taken at E=5.776 GeV beam energy and hatched lines at 5.01 GeV.

B. Targets

E03-103 measured inclusive electron scattering from a wide range of nuclei using both cryogenic and solid targets. This experiment used the standard Hall C target ladder (see Fig. 2) which was placed inside a vertical cylindrical vacuum scattering chamber. The scattering chamber had entrance and exit openings for the beam as well as a vacuum pumping port and several view ports. The beamline connects directly to the scattering chamber, so the beam does not pass through any solid entrance window. There are two cutouts on the chamber for the two spectrometers to detect the scattered particles, which are covered with thin aluminum windows.

FIG. 2: A schematic side view of Hall C target ladder.

TABLE I: Nominal cryotarget dimensions. Here, $\langle t \rangle$ represents the average offset-corrected cryogen in the path of the beam and R.R.L is the relative radiation length which represents the amount of material in the path of the beam.

Target	$\langle t \rangle$ (cm)	Density (g/cm^3)	Areal thickness (g/cm^2)	R.R.L (%)	Purity (%)
^{1}H	3.865	0.0723	0.2794(36)	0.456	99.99
^{2}H	3.860	0.167	0.6446(83)	0.526	99.95
^{3}He	3.865	0.0708	0.2736(51)	0.419	99.9
^{4}He	3.873	0.135	0.5229(85)	0.554	99.99

The target assembly contains several loops for cryogenic targets and the solid target ladder was attached above the optics sled. The target stack can be raised or lowered by an actuator in order to put the desired target in the beam path. The cryogenic targets were contained in vertical cylindrical Al cans with a diameter of ≈ 4 cm. Each loop consisted of a circulation fan, a target cell, heat exchangers and high powered heaters. The target liquid in each loop was cooled with helium gas using a heat exchanger. The liquid moved continuously through the heat exchanger, to the target cell and back. A high power heater regulated the temperature of the cryogenic targets, compensating for the power deposition by the beam during low current or beam off periods. Solid targets were attached above the optics sled and all the foils in the solid target ladder were separated vertically.

The optics sled contained a dummy target, which consisted of two aluminum foils (aluminum alloy Al-6061-T6) placed ~ 4 cm apart. These dummy targets mimicked the cell walls of the cryogenic target and facilitated the measurement of the background originating from the cell walls. The dummy targets were flat aluminum foils and were approximately 8 times thicker than the walls of liquid targets to reduce the time needed for background measurement.

TABLE II: Solid target dimensions, radiation length, and purity. Here, Al(1) and Al(2) represents the aluminum foils which mimicked the cell walls of cryogenic target.

Target	Density (g/cm^3)	Areal thickness (g/cm^2)	R. R. L. (%)	Purity (%)
Be	1.848	1.8703(94)	2.87	99.0
C	2.265	0.6667(40)	1.56	99.95
Cu	8.96	0.7986(40)	6.21	99.995
Au	19.32	0.3795(38)	5.88	99.999
Al(1)	2.699	0.2626(13)	1.09	98.0
Al(2)	2.699	0.2633(13)	1.10	98.0

Areal thicknesses of the cryotargets were computed (see Table I) from the target density and the length of the cryogen in the path of the beam. Since the target cans are cylindrical, the effective target length seen by the beam differs from the diameter of the can if the beam does not intersect the geometrical center of the targets, and a correction accounting for beam offset is applied run-by-run. The target density was calculated using the knowledge of temperature and pressure. Fluctuations in the beam position can also affect the effective target length over the course of the run. This was computed on a run by run basis and applied to all the cryotargets.

Thicknesses of the solid targets were calculated using measurements of the mass and area of the targets. For solid targets, there is an uncertainty in the effective thickness due to uncertainty in angle of the target relative to beam direction, but this is estimated to be $< 0.01\%$. Solid targets used in the experiment and their dimensions are given in Table II. No correction is applied for the $\sim$1% contamination of the ^{9}Be target, as the cross section per nucleon for ^{9}Be and heavier nuclei differs at the few percent level, so the correction is typically $\ll$0.1%.

C. High-Momentum Spectrometer

E03-103 used the HMS to detect the scattered electrons from the interaction vertex. The HMS is a 25° verticalbend spectrometer that consists of three quadrupole magnets, one dipole magnet and a detector package. The detectors are housed inside a concrete enclosure and this shield hut is mounted on a steel carriage which can be rotated on a pair of concentric rails to the desired scattering angle. An octagonal collimator is placed before the entrance to the first magnet which is used to define the acceptance for a short target for particles within approximately 10% of the central momentum setting. A schematic side view of the HMS is shown in Figure 3. All magnets in the HMS are superconducting and are cooled with 4K liquid helium. The focusing properties and acceptance of the HMS are determined by the quadrupole magnets, and the central momentum is determined by the dipole. See Ref. [73, 74] for more details on the spectrometer and detector package.

There are two vertical drift chambers in the HMS located at the front of the detector stack [75]. The drift chambers are used to find the position and trajectory of the particle at the focal plane, which are used to reconstruct the position and momentum of the scattered particle at the interaction vertex. Two sets of $x-y$ scintillators hodoscopes were used for triggering and time-of-flight measurements [**?**]. The detector stack also contains a threshold gas Čerenkov counter used for electron identification [**?**]. The HMS Čerenkov detector is a large cylindrical tank (inner diameter $\approx$ 150 cm and length $\approx$ 165 cm). It has two front reflecting mirrors which focus the light onto two PMTs. The circular ends of the tank are covered with 0.1 cm aluminum windows. For E03-103, the detector was filled with 5.15 psi ($\sim$ 0.35 atmospheres) of Perfluorobutane (C_4F_{10}) at room temperature. At this pressure and temperature, the index of refraction of the gas is 1.00050, yielding a threshold momentum of 16 MeV for electrons and 4.4 GeV for pions. The pion threshold was above the momentum range of E03-103 except for the lowest angles, where the π/e ratio is lower and the separation between electrons and pions in the calorimeter is sufficient to yield a negligible pion background.

A lead glass calorimeter detector [76] was used in conjunction with the Čerenkov detector for electron identification. The HMS calorimeter consists of 10 cm$\times$10 cm$\times$70 cm blocks of TF-1 lead glass, positioned at the rear of the detector hut. The blocks are arranged in four layers with 13 blocks per layer for a total thickness of 16 radiation lengths, along the particle direction. Electrons or positrons entering the calorimeter deposit their entire energy, and the normalized energy spectrum, $E_{cal}/E^{'}$, is peaked around 1. Pions typically deposit $\sim$ 300 MeV in the calorimeter and the $E_{cal}/E^{'}$ distribution peaks around 0.3 GeV/$E^{'}$.

FIG. 3: A schematic side view of the HMS.

III. DATA ANALYSIS

The data acquisition system used for E03-103, was the CODA (CEBAF Online Data Acquisition) software package. CODA events from the individual run files were decoded by the standard Hall C replay software. It reads the raw data written by the data acquisition system, decodes the detector hits, locates possible tracks and particle identification information for each event, and calculates different physics variables. Input and output of the ENGINE are handled using the CEBAF Test Package (CTP). ENGINE makes use of CERN HBOOK libraries and provides output as ASCII report files (scalers, integrated charge . . .), histogram files (ADC/TDC spectra for different detectors) and the reconstructed event-by-event data as ntuples. Detailed cuts, corrections and other analysis details will be discussed in the following sections.

A. Methodology of Cross Section Extraction

The measured inclusive electron scattering cross section at scattered electron energy E' and a central angle θ_c is extracted using

$$\sigma^{Born}_{data}(E',\theta_c) = \frac{Y_{data}}{Y_{sim}}\,\sigma^{Born}_{model}(E',\theta_c) \qquad (10)$$

where $\sigma^{Born}_{data}(E',\theta_c)$ denotes the differential cross section $\frac{d^2\sigma(E',\theta_c)}{dE'd\Omega}$, Y_{sim} represents the simulated yield which includes the features of the detector acceptance and the model radiated cross section, Y_{data} is the charge normalized yield integrated over the acceptance of the experiment and $\sigma^{Born}_{model}(E',\theta_c)$ represents the Born model cross section. To the extent that the simulation properly includes the corrections, efficiencies, and acceptance, the ratio of experimental yield to simulated yield will simply reflect the error in the initial cross section model.

Y_{data} is simply the number of detected electrons, averaged over the kinematics, divided by the efficiency- and deadtime-corrected luminosity of the measurement, so that Y_{data} represents the normalized yield for an ideal detector averaged over the acceptance of the experiment. The calculation of Y_{sim} must yields the same acceptance-averaged normalized yield, and so must include a detailed model of the acceptance as well as all of the physics effects required to go from the starting Born cross section model to the final observed counts, i.e. radiative correction, multiple scattering, energy loss, etc.... In addition, because this is the integrated yield over the acceptance, the cross section model must do a reasonable job of accounting for the cross section variation across the acceptance. Note that the *position-dependent* inefficiencies are applied to the simulation, rather than the data, as discussed in Sec. III B 4, and that while the energy loss is included event-by-event in the simulation, a nominal correction for the median energy loss is applied to both the data and simulation to remove the average kinematic offsets.

1. Extraction of experimental yield

Each kinematic setting contains data taken over one or more runs. Each run is analyzed separately, with detector and acceptance cuts applied and the efficiency and other experimental correction factors calculated run-by-run. The efficiency-corrected and charge-normalized yield for all the runs in a given setting, with

$$Y_{data}^{tot} = \frac{\sum_i N(i)}{N_{sc}\ \sum_i C_{data}(i)\, Q_{tot}(i)}, \tag{11}$$

where N_i is the total number of events which passes all cuts for i^{th} run in the given setting, $Q_{tot}(i)$ is the total accumulated charge and N_{sc} is the number of scattering centers in the target; $N_{sc} = \rho t N_A/M$ where ρ is the density, t is the thickness, M is the atomic mass of the target and N_A is Avogadro's number. The factor $C_{data}(i)$ in Eq. 11 is the correction factor which includes experimental efficiencies and live times; $C_{data} = PS/(\varepsilon_{trig} \times \varepsilon_{track} \times \varepsilon_{det} \times t_{comp} \times t_{elec})$ where PS is the prescale factor used to reduce the trigger rate when the data is taken, ε_{trig} corrects for the events lost due to inefficiency at the trigger level, ε_{track} is the tracking efficiency, ε_{det} denotes the global detector efficiencies, and t_{comp} and t_{elec} are the computer and electronic live time, respectively.

Because we are only interested in primary beam electrons which scatter in the target, we have to subtract the contribution of electrons which scatter in the target entrance and exit windows (for the cryogenic targets) and secondary electrons which come from other processes. The subtraction of the cryotarget endcap contribution is discussed in Sec. III C 1, and the secondary electrons in Sec. III C 2.

2. Extraction of simulated yield

In order to evaluate Y_{sim} one needs to account for the finite acceptance of the HMS using a detailed model of the spectrometer acceptance. Cuts are applied to the measured and simulated distributions to limit the data to events where the momentum acceptance is well understood. These cuts, given in Table III are large enough in angle so that the collimator defines the angular acceptance, but are effective in removing in-scattering events which reconstruct to trajectories outside of the acceptance.

TABLE III: Acceptance cuts used in the analysis for data and simulation. Here, δ is the relative deviation from the central momentum and x'_{tar} and y'_{tar} are the out-of-plane and in-plane angles of the reconstructed tracks.

Variable	cut value
abs(δ)	$< 9\%$
abs(x'_{tar})	< 120 mrad
abs(y'_{tar})	< 40 mrad

An acceptance function is generated and applied to the simulation to account for the finite acceptance of the spectrometer. This function is defined to be the probability that the spectrometer will accept an event originating from a point in the target $(x_{tar}, y_{tar}, z_{tar})$ with momentum and angles described by three spectrometer coordinates $\delta, x^{'}, y^{'}$. In general, the acceptance is a function of the six variables $(\delta, x^{'}, y^{'}, x_{tar}, y_{tar}, z_{tar})$ that fully define the event, and is generated by Monte Carlo. It is not feasible to generate the full six-dimensional acceptance function, but it can be simplified by integrating over variables. Because the yield is the acceptance-weighted cross section, we can average over variables which do not impact the cross section or which are uniformly populated. Since there is no significant loss of beam intensity along the target, the distribution in z_{tar} is uniform, so the acceptance function can be integrated over z_{tar}. Similarly, we do not bin in the target x or y positions, and so we can integrate the acceptance function over a range in target position that corresponds to the observed position and raster size of the beam. Note that while we do not bin the data in the target position variables, we do use the reconstructed vertical target position to calculate a small correction to the reconstructed momentum of the event in both the data and simulation. This yields an acceptance function that depends only on the trajectory of the event at the target, $A(\delta, x', y')$, the same subset of target variables that go into the cross section model. If instead we write the acceptance and cross section as a function of the scattering angle, θ, and azimuthal angle, ϕ, the inclusive cross section depends only on E' and θ, and so the acceptance function can be integrated over ϕ, yielding a two-dimensional acceptance function. The acceptance function is then calculated using a realistic distribution of event positions in the target, meaning that it must be calculated separately for each effective target length as seen by the spectrometer, i.e. separate for point-like and extended targets, and for each different spectrometer scattering angle.

The final yield is an integral of the acceptance function over the phase space, weighted by the differential cross section:

$$Y_{sim} = \int dE' d\theta \; \varepsilon'_{det} \; A(E', \theta) \sigma^{rad}_{model}(E', \theta, \phi) \; , \quad (12)$$

where ε'_{det} accounts for any position-dependent efficiencies in the detectors and σ^{rad}_{model} is the cross section model, including radiative effects.

The Hall C single arm Monte Carlo was used for the acceptance calculation. Each event is randomly generated in the target coordinates, while the quantities δ, y', x' are randomly chosen within their allowed limits. Then the particles are projected forward and transported to the detector hut using transport matrix elements calculated by the COSY INFINITY program [77], which models magnetic transport properties of the spectrometer. Events that fail to pass through the different apertures defined in the model are rejected. Multiple scattering is simulated as the electrons pass through material in the spectrometer, and so the acceptance function is generated for each spectrometer momentum setting to account for the energy-dependence of the scattering. If the particle successfully traverses the spectrometer and passes all the criteria in the detector then it is accepted.

After applying cuts and binning the Monte Carlo counts in the same manner as data, the acceptance function is simply the fraction of events in a given bin that were accepted and passed all cuts. The integral in Eq. 12 is evaluated in each bin, Thus the weighted, simulated yield in Eq. 12 for a particular (E', θ) bin is given by

$$Y_{sim}(E', \theta) = \sum_{events} \varepsilon'_{det} \sigma^{rad}_{model}(E', \theta) \; (\Delta E' \Delta \Omega)_{bin} \quad (13)$$

where $(\Delta E' \Delta \Omega)_{bin} = (\Delta E' \Delta \Omega)^{gen}_{bin} / (N^{gen}_{bin})$ represents the relative phase space for a given event in the bin. The generated solid angle depends on the generation limits in x'_{tar} and y'_{tar}. In this analysis 5×10^6 events were generated for each simulated ntuple with generation limits $\delta = \pm 15\%$, $x'_{tar} = \pm 100 \; mr$ and $y'_{tar} = \pm 50 \; mr$. Once the measured and simulated yields yield have been obtained, the yield ratio is applied as a correction factor to the initial Born cross section used in the simulation to extract the final cross sections (Eq. 10).

B. Efficiencies

In the cross section analysis, we apply particle identification (PID) cuts on the signals from the gas Čerenkov counter and lead-glass calorimeter to distinguish electrons from other negatively charged particles. Because of this, we must also correct for losses of real events when these cuts are applied arising from detector-related inefficiencies. There are additional losses due to trigger inefficiency or inefficiency of tracking algorithm to find a valid track. Finally, the calorimeter and Čerenkov detectors are used to reject pions, and the pion rejection cuts can yield a small electron inefficiency.

1. Trigger efficiency

The trigger was designed to be efficient for electrons while suppressing other particle types. The electron trigger is described in detail elsewhere [73, 78, 79], and the key points are summarized here. There are two main electron triggers. The first requires signals from 3/4 hodoscope layers and a signal from the calorimeter. The second requires a Čerenkov signal and either 3/4 hodoscope planes or 2/4 planes (one from the front and one from the back) and a calorimeter signal with a lower threshold than the other trigger. This way, even if the Čerenkov or calorimeter have low efficiency, or the 3/4 hodoscope efficiency falls, we still maintain a high trigger efficiency based on the other two detectors.

Because there were no problems with the operation of the detectors, the final trigger level efficiency was extremely high. The efficiency for a good event to give signals in 3 of the 4 hodoscope planes was determined run-by-run, and found to be 99.2% on average. The efficiency for the time-of-flight trigger (two planes, one in front, one in back) was 99.7%. While the time-of-flight trigger required both a signal from the calorimeter and Cerenkov detectors, the 3/4 required only one PID signal, making the trigger efficiency high even if one of the detectors had a low efficiency. Accounting for all of these effects, the trigger efficiency is 99.7% [79], and was largely rate and kinematic independent, yielding a negligible uncertainty in the cross section ratios.

2. Tracking efficiency

The normalized yields must also be corrected for inefficiencies in the tracking. The tracking efficiency is defined as the fraction of good events which yield a valid track. A track can be lost to hardware inefficiency or failure in the tracking algorithm, often due to missing planes or excess noise or background hits. The tracking efficiency correction was applied on a run-by-run basis. At low rates, the efficiency was approximately 98%, with a small reduction at high rates (up to 2%) which is consistent with the expected loss due to rejection of events with real multiple tracks.

3. Calorimeter cut efficiency

To reject pions, we require that the energy deposited in the calorimeter be at least 70% of the reconstructed momentum ($E_{cal}/E^{'}>0.7$). It is important to know how many otherwise valid events are lost when we place a cut on the calorimeter distribution. To determine the fraction of electrons lost due to the calorimeter cut, we need to identify a clean and unbiased sample of electrons. For this analysis, we used elastic scattering data, where the initial fraction of pions is small, and then apply a cut on Čerenkov detector to yield a pure electron sample. While elastically scattered electrons tend to populate a limited region in the acceptance of the spectrometer, this region can be moved across the acceptance by changing either the angle or scattered electron momentum, allowing us to map out the response of the spectrometer throughout the acceptance. We use these scans to verify that the cut efficiency is uniform across the acceptance. The efficiency is found to be constant for E' above 1.7 GeV (99.89%), but below this momentum, the efficiency starts to decrease mainly due to decreasing resolution of the calorimeter. This falloff is approximately linear, dropping the efficiency by 0.3% for $E' \approx 0.7$ GeV/c [79] and is parameterized as a function of the scattered electron momentum and is used to correct data in the analysis. The efficiency measured with elastics is consistent with the efficiency extracted using inelastic kinematics which populate the full acceptance, where the kinematics have few enough pions for the Čerenkov to yield a pure electron sample.

4. Cerenkov cut efficiency

Another cut was applied on the number of photo-electrons collected by the Čerenkov detector in order to distinguish electrons from pions. In addition to the pion-rejection cut in the calorimeter, we also require the Čerenkov detector sees at least 1.5 photo-electrons. To measure the electron efficiency of this cut, we generate a pure sample of electrons using elastic scattering kinematics along with a cut on the calorimeter.

During the analysis it was found that the signal from the Čerenkov detector was lower near the vertical center of the detectors, corresponding to $\delta = 0$. This is due to the gap between the upper and lower mirrors. In addition to this δ-dependent inefficiency, the Čerenkov has a momentum-dependent inefficiency due to variation of Čerenkov cone with particle momentum. The efficiency was parameterized in terms of both δ and the HMS momentum setting. The efficiency is close to 100% for momenta above the central momentum setting, 1–2% lower on the low-momentum side of the acceptance, with loss of up to 2–4% efficiency in the central ±0.5% of the momentum acceptance (the inefficiencies are larger at low momentum settings). For details, see Ref. [79].

C. Backgrounds

In addition to the scattered electrons, there are secondary electrons that are in the acceptance of the detector due to other physical processes which constitute a background for the measurement. This background mainly consists of scattered electrons from the cryotarget cell wall, pions that survive the nominal PID cuts and are treated as scattered electrons, and secondary electrons from pair production after bremsstrahlung in the target or π^0 which decay to photons. The following subsections discuss each of these processes, and how we estimate and correct for them in the analysis.

1. Background from target cell wall

Since the cryogenic targets were contained in aluminum cells, electrons scattered from the cell walls also contribute to the total number of detected events. This contribution is measured and subtracted from the total detected events. The cryocells were made of Al 7075 which has a density of 2.7952 g/cm^3 and the thickness of the cell walls was ∼0.12 mm. The electrons traverse two cell walls, and since the cryotarget thickness varies between 0.2 to 0.6 g/cm^2, the typical size of the background contribution is between 10% to 20%. We used a dummy aluminum target to directly measure the cell wall contribution to the total yield. The dummy target consists of two Al foils (Al 6061- T6) separated by ∼4 cm which are ∼8 times thicker than the cryocell walls, thus allowing a higher luminosity and a smaller data acquisition time. During the experiment dummy data were taken at the same kinematics as the cryotarget data. Dummy data are treated in the same way as cryotarget data and the normalized dummy yield is subtracted from the cryotarget yield. Thus the total yield is

$$Y = Y_{cryo} - \left[\frac{R^{ext}_{dummy}}{R^{ext}_{walls}} \frac{T_{walls}}{T_{dummy}} \right] \times Y_{dummy}, \qquad (14)$$

where T_{walls} and T_{dummy} are the thicknesses of the cell walls and the dummy respectively, Y_e and Y_{ed} are the measured cryotarget yield and dummy yield respectively, and the ratio of R^{ext}_{dummy} and R^{ext}_{walls} represents a correction factor which is applied to the radiative corrections of the dummy yields. This correction factor is due to the difference in thickness between dummy and the cryotargets which modifies the external bremsstrahlung. The correction was found to be about 5% for larger scattering angles at low x values and smaller for other angles.

2. Charge symmetric background (CSB)

At low x and high Q^2, there is a significant probability that the incident electron can interact with the target nuclei and produce neutral pions in the target. These pions can decay into high energy photons which produce an equal number of positrons and electrons. The total number of electrons detected in the spectrometer is $e^-_{detected} = e^-_{primary} + e^-_{background}$. Since an equal number of positrons and electrons are produced, the yield is charge symmetric. This allows us to estimate the number of secondary background electrons by running the spectrometer with positive polarity and detecting the positrons. During E03-103, we used the HMS to take positron data for each target at all kinematics setting where the CSB was significant, allowing for a direct subtraction of the background by assuming $e^-_{background} = e^+_{detected}$. Luminosity normalized yields are used to subtract the CSB, with identical cuts applied to the positron and electron data. R_{csb}, the fraction of the detected electrons associated with CSB, is shown in Fig. 4 as a function of x for the 50 and 40 degree data. Note that our final EMC ratios are formed from the 40 degree data, and so the correction is below 10% except for the smallest values of x and the high-Z targets.

3. *Pion backgrounds*

Pion rejection factors for the Čerenkov and calorimeter detectors are always greater than 500:1 and 100:1, respectively. Nonetheless, for runs with a high π/e ratio, there could still be a small contamination of pions after the PID cuts.

To estimate the pion background for high π/e kinematics, we generate calorimeter spectra for electron runs (including all of the PID cuts except the software calorimeter cut), and pure pion spectra (using runs without trigger-level PID and requiring less then 0.5 photoelectrons in the Čerenkov. The pion sample is renormalized to match the pion background in the 'electron' sample at $E_{cal}/E'{<}0.7$, and the tail of the pion spectrum extending to $E_{cal}/E'{>}0.7$ is used to estimate the pion contamination after all PID cuts. It was found that the final pion contamination is always below 0.5%. This is further suppressed as the subtraction of the positive-polarity data intended to remove charge-symmetric backgrounds (see section III C 2) will have a nearly identical contribution from positive pions. We estimate that any residual pion contamination is extremely small, and so we do not apply any correction, but assign a 0.2% point-to-point uncertainty to allow for a small net contribution of pions.

D. Target boiling corrections

When the electron beam passes through the target material of cryogenic targets, it deposits energy in the form of heat. This causes local density fluctuations, "target boiling", along the path of the beam. The boiling effects depend on the beam current, beam raster size and the thermal properties of targets. We perform luminosity scans, measurements of the yield at fixed kinematics with varying beam currents, to estimate the boiling effects. In addition to measuring the effect on the cryogenic targets, we also take data on carbon as a reference measurement, to insure that corrections for rate-dependent effects do not introduce variations which are misinterpreted as density fluctuations.

A small current dependence was observed for the carbon target, even after correcting for all known rate-dependent effects. Because the beam-current monitors have an uncertainty in their DC offset, an error in that offset can yield an error in the charge that goes like the

FIG. 4: The charge symmetric background as a function of x for data taken at 50 degrees (top) and 40 degrees (bottom).

inverse of the beam current. The effect in carbon was small enough to be consistent with the uncertainty in the BCM offset uncertainty, and so the current dependence in the cryogenic targets were taken relative to the carbon results to remove this effect. The hydrogen and deuterium targets did not show any residual slope after correcting for the BCM offset, but the helium targets show a linear drop in the yield. For ^{3}He, the measured density loss was $(-3.10 \pm 0.64)\%$ at $100\,\mu A$ and for ^{4}He, $(-1.27 \pm 0.50)\%$ at $100\,\mu A$. The yield for each run is divided by a correction factor which depends linearly on the average current (excluding periods with no beam).

E. Computer and electronics deadtimes

Events are also lost due to the finite time it takes to either form a trigger for an event or read out the data. During the time the trigger or DAQ systems are busy, no new events can be taken. This is monitored on a run-by-run basis by looking at the number of events generated with final trigger module widths of 50, 100, 150 and 200 ns, and the electronic deadtime scales with the trigger rate and gate width except for the 50 ns measurement. While the typical gate widths are 40 ns, the coincidences formed between different hodoscope planes have variable widths, typically 50-60 ns, so our final trigger module is set to 60 ns to minimize the event-to-event variation of the effective latency time. We calculate and apply a deadtime correction of 60 ns time the raw pretrigger rate, yielding a maximum correction of 1.5%, but typical values well below 0.5%.

Computer deadtime occurs when the DAQ computers are busy processing events (either digitizing fastbus information or sending the data to the DAQ computers), and are not available for processing new events. Because the events are buffered in the fastbus and VME modules, there is not a fixed latency period for each event, so we make a direct measurement of the computer deadtime and apply the correction on a run-by-run basis. We take the number of events recorded to disk divided by the number of generated triggers which should have been read out and take the ratio to be the live time. The deadtimes were kept below 20% by adjusting the prescale factors, although previous tests have shown reliable operation and corrections for deadtimes well over 90% [73].

F. Cross Section Model

A cross section model is required for the bin centering corrections, the radiative corrections and the Coulomb corrections. The Born cross section model (known as XEM model) is broken down into contributions from inelastic and quasielastic scattering:

$$\sigma_{Born} = \sigma_{inel} + \sigma_{qe}\ . \tag{15}$$

For the quasi-elastic contribution σ_{qe}, we use a y-scaling model. The scaling variable y can be interpreted as the minimum momentum of the struck nucleon in the direction of the virtual photon. The scaling function, $F(y)$, is an energy and momentum integral of the spectral function and is defined as the ratio of the measured nuclear cross section to the off-shell cross section for a nucleon, multiplied by a kinematic factor [73, 80, 81]:

$$F(y) = \frac{d\sigma}{d\Omega d\nu} \frac{1}{\mathrm{Z}\sigma_p + \mathrm{N}\sigma_N} \frac{q}{\sqrt{M^2 + (y+q)^2}}, \tag{16}$$

where Z is the number of protons in the nucleus, N is the number of neutrons, q is the three-momentum transfer, and M is the proton mass. $F(y)$ is expected to scale in y on the low energy loss side of the quasielastic peak where inelastic contributions and final state interactions are minimal. The scaling function used for ^{2}H is from [82] and has the form:

$$F(y) = (f_0 - B)\frac{\alpha^2\, e^{-(ay)^2}}{\alpha^2 + y^2} + B\, e^{-b|y|}. \tag{17}$$

For heavier targets this was modified to be:

$$F(y) = (f_0 - B)\frac{\alpha^2\, e^{-(ay)^2}}{\alpha^2 + y^2} + B\, e^{-(by)^2}, \tag{18}$$

where the parameters a, b, f_0, B and α are fit to the $F(y)$, extracted from the data for each target. The model parameters were varied to reproduce the data from this measurement, along with the measurements covering $x \gtrsim 1$ on the same targets from Refs. **??**. The model was also compared to low Q^2 quasielastic data, taken from Ref. [83], because of the importance of events from low Q^2 quasielastic scattering, which has a large cross section, radiating down into the lower x kinematics for this experiment.

F(y) was extracted from the data in the QE region after subtracting the inelastic contribution (calculated using the inelastic part of the model) [81]. After fitting F(y), the updated model was used as the input for the cross section extraction, and the process was repeated until good agreement between data and the model was achieved for all settings. In addition, an angle independent global polynomial correction was used for each target to improve the agreement between data and model.

For the deuteron, parameterizations of the proton and neutron structure functions (developed by P. Bosted and E. Christy [84]) are used for the full x range. They are smeared using the momentum distribution based on the fit to our QE peak [81].

For heavier nuclei, the inelastic cross section is computed differently. For $x < 0.8$, the inelastic cross section is built from the ^{2}H model using the 'inelastic' EMC ratio obtained from our data. These inelastic ratios are obtained from the data by subtracting the quasi-elastic model from the cross section; the subtraction is negligible at high Q^2, where we quote our EMC ratios, but is more important for the low Q^2 model. For $x > 0.9$, the smearing prescription is used with the corresponding momentum distribution for each target, and a linear interpolation between the two parts of the model is used between $x = 0.8$ and 0.9.

The inelastic part of the model used for radiative correction is slightly different from the model above. The inelastic model used for bin centering has the disadvantage that, at low Q^2, the resonances do not get smeared out enough, leaving some residual structure in the data to model ratios. For the radiative corrections therefore it was decided to use the smearing prescription for the full x range. For $x < 0.8$, the model is the sum of the proton and neutron structure functions smeared by the momentum distribution. For $x < 0.8$, this inelastic model is then multiplied by a target-dependent polynomial function to improve the agreement between data and model. This is smoothly joined to the full smearing prescription for $x > 0.9$, using an x-weighted average for $0.8 < x < 0.9$. For the bin centering, we need the Born cross section on a two dimensional grid in θ and x (or $E^{'}$), and the smearing prescription for the inelastic model cannot be used because of the significant increase in CPU time. However, once the bin centering corrections are applied, the data are centered to the central angle. Hence, the radiative correction table can be one dimensional, since the data are centered to the central angle of the setting. The data as well as the model cross sections, including the relative contributions from the inelastic piece and the quasielastic piece for ^{2}H and ^{197}Au are shown in Fig. 6.

At low Q^2 values, the quasi-elastic peak accounts for a significant portion of the total cross section at large x. The low-Q^2 QE cross section also has a large impact on the radiated model at low x and high Q^2. We have done extensive studies and compared our model with the data available from the quasielastic electron nucleus scattering archive [83]. For heavy nuclei, our model cross section was compared with world QE data down to $Q^2 = 0.5$ GeV^2, and the agreement between data and model was found to be at the 10% level near the quasielastic peak, as shown in Fig 5.

G. Other corrections

The XEM cross section model is in the Born or one-photon exchange approximation. However, higher order processes in α also contribute to the measured cross sections [85, 86] and must be applied to the starting model. To compare to the measured cross sections, all significant contributions from higher order processes must be estimated and corrected for in the measured cross section. These include traditional radiative corrections, as well as the "Coulomb corrections" associated with the long-range interaction of the electron with the charge of the nucleus.

FIG. 5: Comparison of world data from the quasielastic electron nucleus scattering archive [83] and our cross section model for a variety Q^2 settings (average Q^2 values quoted is for the quasielastic peak) for the ^{2}H (top) and ^{197}Au targets. The shape of the QE peak is well reproduced for both targets at both low and high Q^2, yielding a nearly flat ratio of data/model over the entire x range.

H. Radiative corrections

Radiative corrections need to be applied to account for higher order QED diagrams, the most significant of which are the emission of one or more real photons by the incoming or outgoing electron or the struck quark (in the DIS regime), exchange of a virtual photon between the incoming and outgoing electron, and the fluctuation of

FIG. 6: Data and model cross section for ^{2}H and ^{197}Au at selected kinematics. Here, the circles shows 18 degree data and the squares shows 50 degree data. Relative contribution from inelastic (dashed line) and quasielastic (dotted line) to the total cross section (solid line) are also shown in the figure.

the exchange photon into a lepton-antilepton pair. Because the elastic and quasielastic cross sections are very large at low Q^2, one must also account for low-Q^2 interactions which, due to radiation of a hard photon, end up at low x and high Q^2 values. Thus, we express the total radiated cross section as:

$$\sigma_{measured} = \sigma^{radiated}_{inelastic} + \sigma^{radiated}_{quasielastic} + \sigma^{radiated}_{elastic} \quad . \qquad (19)$$

Since the inelastic radiative cross section is largely proportional to the Born cross section for our kinematics (>80%), we used the multiplicative radiative correction method. For the kinematics of this analysis, our studies indicate that the nuclear elastic tail contributes less than 0.1% to the total cross section for ^{2}H, and significantly smaller contributions for heavy nuclei, and so are neglected in the analysis.

The program used to compute the radiative corrections for this analysis was developed at SLAC and is described in detail in [87]. For E03-103, the external corrections are computed using a complete calculation of Mo-Tsai [85] with a few approximations. Note that, in particular, the energy-peaking approximation is not used for the computation of external contributions. This approach, "MTEQUI", uses the equivalent radiator approximation [87]. In the equivalent radiator method, the effect of "internal" Bremsstrahlung is calculated using two hypothetical radiators of equal radiation length, one placed before and one after the scattering. The internal contribution in "MTEQUI" method is evaluated by setting the radiation length of the material before and after the scattering point to zero, and ignoring the target length integral. Then the radiated model cross section is given by the sum of the internal and external contributions.

Our simulations are performed using the radiated model,

$$\sigma^{model}_{radiated} = external \otimes internal \otimes \sigma^{model}_{Born}\,, \qquad (20)$$

is the model cross section due to the sum of all higher-order diagrams. The convolution involves integrating over the "internal" and "external" bremsstrahlung photon momenta and angles, and the target dimensions. To obtain $\sigma^{model}_{radiated}$, one needs to know the cross sections over the entire kinematic range (from elastic threshold up to the kinematic point being calculated, see Figure C.1 in reference [87]). The effect of radiative correction on measured cross sections varied from a few percent to about 40%, depending on the kinematics and targets. Because the structure functions of nuclei are very similar, the internal radiative corrections and some of the external corrections cancel, yielding smaller corrections in the target ratios which depend mainly on the difference in the targets radiation length, as shown in Fig. 7.

I. Coulomb corrections

The incoming electron will interact with the Coulomb field of the nucleus prior to interacting with the nucleus. Classically, once the electron enters the electron cloud of the atom, the screening of the nuclear potential is no longer perfect, and the electron will be accelerated towards the nucleus, increasing its momentum at the interaction vertex. After the scattering, there will be a similar interaction as the electron leaves the nucleus. This change in the kinematics can have a significant effect on the measured cross sections if either the Coulomb potential is large compared to the energy of the initial or final

FIG. 7: Radiative correction factor to the A/D cross section ratios for a range of targets at 40 degrees; the correction at 50 degrees is nearly indistinguishable.

electron, or when the cross section varies rapidly with the kinematics. In addition to the modification of the scattering kinematics there is also a 'focusing' of the incoming electron plane wave which also impacts the scattering cross section. For the present analysis, we account for these effects using the improved version of the Effective Momentum Approximation (EMA) described in Ref. [88].

The charge of the nucleus has two effects on the electron wave function. The initial and final state electron momenta ($\vec{k}_{i,f}$) are modified in the vicinity of the nucleus due to the attractive electrostatic potential. Secondly, the attractive potential leads to focusing of the electron wave function in the interaction region. The distorted electron wave can be approximated by [89, 90],

$$\psi_{\vec{k}_{i,f}} = \frac{|(\vec{k}_{i,f})_{eff}|}{|\vec{k}_{i,f}|} \, \psi_{(0)} \, \exp\left(i \, \vec{k}_{i,f} \cdot \vec{r}\right), \qquad (21)$$

where $\psi_{(0)}$ is the Dirac-spinor with $|(\vec{k}_{i,f})_{eff}| = |(\vec{k}_{i,f})| - \overline{V}$, and $\overline{V}$ is the average electrostatic potential of the nucleus. The change in potential for a highly relativistic electron approaching from infinity along the z axis towards the center of a spherical charge distribution with charge Ze, radius R_0, is given by:

$$\Delta V_{(z)} = V_{(\infty)} - V_{(z)} = -\frac{Z\alpha}{2R_0}\left(3 - \frac{z^2}{R_0^2}\right) \qquad (22)$$

(for $z < R_0$) with $V_{(\infty)}$ defined as zero and z measured from the center of the sphere. The RMS charge radii of a nucleus with mass number $A > 4$ are calculated using the relation given in [90],

$$R_0(A) = 1.1 \, A^{1/3} + 0.86 \, A^{-1/3}. \qquad (23)$$

Because one does not correct for Coulomb acceleration in $Z = 1$ targets, we replace the factor Z with $Z - 1$ in Eqn. 22 to account only for the additional charge in the nucleus compared to scattering from the proton or deuteron. This is a modification of the procedure of Ref. [90], but because the potential is determined in that analysis for heavy nuclei, the change from Z to $Z-1$ has an extremely small effect in the determination of $\Delta V_{(z)}$, but does modify the correction for low-Z nuclei.

TABLE IV: Table shows the average effective potential ΔE and the values of RMS charge radii for the different targets used in the analysis. The radii for ^{3,4}He are measured values while the rest are based on Equation 23.

Target	R_0 (fm)	ΔE (MeV)
^{3}He	1.80	0.85
^{4}He	1.68	1.0
^{9}Be	2.70	1.88
^{12}C	2.89	2.92
^{63}Cu	4.59	10.2
^{197}Au	6.55	19.9

Since most of the nucleons in a heavy nuclei are located on the surface of the nucleus, taking the electrostatic potential at the center of the nucleus will be an overestimate of the Coulomb correction. This effect is incorporated in the EMA approach by an average potential 0.75-0.80 times the central potential, $V_{(0)}$. For E03-103, an average potential of $\Delta E = \overline{V} = 0.775 V_{(0)}$ is used and we estimate this to be known at the 10% level.

In the EMA approach, the focusing factor of the incoming wave, $F_i = |(\vec{k}_i)_{eff}|/|\vec{k}_i|$, enters quadratically in the cross section calculation and produces an enhancement in cross section strength. However, the focusing factor of the outgoing wave cancels with the enhanced phase space factor in the effective cross section. The Coulomb correction factor in the EMA approach is given by the ratio of the model cross sections with nominal and shifted kinematics, scaled by the square of the focusing factor:

$$F_{ccor} = \frac{\sigma_{(E,E')}}{\sigma_{(E+\Delta E,\, E'+\Delta E)}} \left[\frac{E}{E+\Delta E}\right]^2, \qquad (24)$$

where σs are the Born model cross sections. The measured cross sections are then multiplied by F_{ccor}, to get the Coulomb-corrected cross sections.

Table IV shows the values for the RMS charge radii, and the magnitude of the average energy boost for the targets used in E03-103. The Coulomb correction factors as applied to the data are shown in Figure 8. This figure shows the importance of the Coulomb distortion effects

FIG. 8: Coulomb correction factors as a function of x for several targets as noted in the legend for a few selected kinematics for 5.776 GeV beam energy. Here, the filled symbols represent 50 degree data while the open symbols represent 18 degree data.

for the cross section and cross section ratio extractions in the medium energy range. These are relatively small for light nuclei, but for the heavy nuclei and near the quasi-elastic peak, these corrections are significant. The largest corrections are for the Au data at 40 and 50 degrees. With no Coulomb corrections applied, the EMC ratios are systematically 3-5% higher for the 50 degree data. After applying the EMA corrections described above, the data are in excellent agreement, suggesting that the correction yields agreement at the 2% level or better, given the uncertainties in the comparison. This supports the idea that the EMA does a good job estimating this correction, though it assumes that no other effect modifies the cross section ratios in going from 40 to 50 degrees. This will be discussed further in Sec. V B.

Since this is a target- and x-dependent correction, neglecting the effect will modify both the extracted size of the EMC effect and the overall A dependence. In addition, for a given x value the angular dependence of the Coulomb correction factor implies a Q^2 dependence in the correction. Thus one should be careful about Q^2 averaging of the cross section or cross section ratios and these correction factor needs to be properly accounted for before applying such an averaging procedure. While Coulomb corrections were not applied to previous EMC measurements, the effect was estimated to be $\lesssim$3% [4] for SLAC E139 [16], owing to the higher beam energy and smaller scattering angles. Nonetheless, neglecting this correction would imply some overestimate of the EMC effect in medium-heavy nuclei. We will discuss this further in the results section.

J. Isoscalar corrections

EMC ratios are expressed as the cross section ratio (per nucleon) of a target nucleus with an equal number of protons and neutrons (isoscalar nuclei) to that of deuterium. Thus, the EMC ratio for an isoscalar nuclei is just σ^A/σ^D. Since the protons and neutrons have different cross sections, the cross sections for nuclei with $Z \neq N$ will significantly differ from that of nuclei with $Z = N$. Thus, one needs a correction function to the measured F_2^A to get a symmetric nucleus:

$$(F_2^p + F_2^n)/2 = f_{iso}^A (ZF_2^p + NF_2^n)/A. \tag{25}$$

This correction function reduces to a function of F_2^n/F_2^p, the neutron to proton structure function ratios of the nucleus under investigation:

$$f_{iso}^A = \frac{(F_2^p + F_2^n)/2}{(ZF_2^p + NF_2^n)/A} = \frac{A(1 + F_2^n/F_2^p)}{2(Z + NF_2^n/F_2^p)}. \tag{26}$$

The measured cross section ratios are multiplied by f_{iso}^A, which depends only on N, Z, and the neutron-to-proton ratio, to get the isoscalar-corrected cross section ratios. Note that the structure functions in Eq. 25 correspond to the proton and neutron contributions to the heavy nucleus, as one is trying to convert from a non-isoscalar heavy nucleus to the isoscalar equivalent. In the past, these were simply replaced with the free neutron and proton structure function ratio.

FIG. 9: The ratio F_2^n/F_2^p vs. x for various parameterizations along with the ratio in deuterium, $\overline{F_2^n}/\overline{F_2^p}$, extracted for the 40 deg kinematics of E03-013 experiment.

There is significant uncertainty in the free neutron cross section in the large x region and so the extracted

EMC ratios are sensitive to the choice of isoscalar correction factor. The F_2^n/F_2^p ratio has been extracted from proton and deuteron DIS measurements by SLAC [91] and NMC [92, 93]. Since there is no free neutron target, the extraction of F_2^n is always model-dependent. The SLAC extraction included Fermi motion while the NMC F_2^n/F_2^p ratios were extracted from neglecting all nuclear effects (including binding) in the deuteron. The EMC effect results from SLAC E139 [16] took $\sigma_n = \sigma_p(1 - 0.8\ x)$ when calculating the isoscalar correction. Figure 9 shows different representative parameterizations for F_2^n/F_2^p along with F_2^n/F_2^p constructed from parton distributions from CTEQ [94] computed at $Q^2 = 10$ GeV^2. The CTEQ fit also neglects the Fermi motion of nucleons. NMC mostly had data in the low x region, however, the x range covered by SLAC data is mainly in the large x region and overlaps with x range covered by E03-103. All of these extractions are based on measurements of the deuteron-to-proton ratios in different Q^2 regions, and so any Q^2 dependence in the ratio would be expected to yield scattering in these results, beyond that associated with differences in the assumptions made in the extraction.

FIG. 10: Our extracted $\sigma^D/2\sigma^p$ ratio along with calculations based on different F_2^n/F_2^p extractions (dashed line from [95] and solid line using [57, 96]. The structure above $x \approx 0.65$, is mainly due to the resonance in the proton structure function.

In our analysis we make a modified isoscalar correction. Instead of using free proton and neutron structure functions, we have used the contributions of F_2^p and F_2^n in ^{2}H (i.e., $\overline{F_2^n}$ and $\overline{F_2^p}$) in the above equation to correct the nuclear cross sections. As such, we are converting the deuteron structure in the denominator to a non-isoscalar deuteron, with the same Z/N ratio as the nucleus. The alternative would be to evaluate the neutron-to-proton ratio for all nuclei, which would involve significantly larger model dependence in heavier nuclei. In addition, we use the n/p ratio at the kinematics of our experiment, rather than taking the result from a high-Q^2 analysis. We determine the in-deuteron n/p ratio following the approach of Refs. [57, 96]. The extraction was performed taking the average of the values obtained using the different NN potentials and off-shell effects evaluated in Ref. [57], using the calculated value of $\overline{F_2^p}$ in the deuteron, and taking $\overline{F_2^n}/\overline{F_2^p} = (F_2^d - \overline{F_2^p})/\overline{F_2^p}$. This does not involve removing the nuclear effects to extract the free neutron structure function, as is usually the case, and so this procedure is somewhat less model dependent than the extraction of the free F_2^n/F_2^p ratio. We note that these analyses also demonstrated that the model-dependence is smaller than assumed in some previous comparisons, as some previous extractions evaluated nuclear effects at different Q^2 values than the data that was used to extract F_2^n/F_2^p. A similar result was seen in the analysis of the impact of nuclear effects on the extraction of the proton pdfs [56].

Figure 10 shows the $\sigma^D/2\sigma^p$ cross section ratios extracted from the E03-103 data for the 40 degree kinematics. Representative extractions [57, 95], of the same ratio is also shown in the figure. It should be noted that the isoscalar corrections depends on Q^2, and this effect is not negligible at large x. The correction factors derived using various parameterizations for ^{3}He and Au are shown in Figure 11.

In the case of ^{3}He, one can avoid the uncertainty associated with the isoscalar corrections by extracting the ratio of ^{3}He to (^{2}H+^{1}H). This ratio and the comparison to the isoscalar-corrected ^{3}He/^{2}H ratio are presented in section V B.

K. Scaling violation effects at high x

As discussed in Sec. I A, deviations from the scaling of the simple quark parton model arise due to QCD evolution of the pdfs, target-mass corrections which involve to finite-Q^2 corrections to the approximations made in the infinite ν, Q^2 limit, and higher twist contributions which go beyond incoherent scattering from individual partons.

The kinematic effects due to target mass corrections were first calculated in the framework of the operator product expansion OPE by [97]. In the nucleon case, the measured structure function F_2^{meas} can be related to the massless limit structure function $F_2^{(0)}$ [3] via

$$F_2^{meas}(x,Q^2) = \frac{x^2}{\xi^2 r^3}F_2^{(0)}(\xi,Q^2) + \frac{6M^2x^3}{Q^2r^4}h_2(\xi,Q^2) + \frac{12M^4x^4}{Q^4r^5}g_2(\xi,Q^2) \quad (27)$$

where $h_2(\xi,Q^2) = \int_\xi^1 du\ u^{-2}F_2^{(0)}(u,Q^2)$, $g_2(\xi,Q^2) = \int_\xi^1 dv\ (v-\xi)v^{-2}F_2^{(0)}(v,Q^2)$, $r = \sqrt{1+\frac{Q^2}{4x^2M^2}}$ and $\xi = \frac{2x}{1+r}$. $F_2^{(0)}$ do not contain target mass effects and this is the function which obeys the QCD evolution effects in the

FIG. 11: Magnitude of isoscalar corrections for ^{3}He (top figure) and Au (bottom figure) targets for the 40 degree data for the different parameterizations of F_2^n/F_2^p as discussed in the text. The solid black line represents the multiplicative correction factors obtained using the smearing method discussed in the text and was used in the E03-103 analysis for the EMC ratio extraction.

absence of higher twist effects. It should be noted that there are different prescriptions [3, 98, 99] available for these kinematical corrections with slightly different end results, however, the appropriate prescription for target mass corrections in nuclei is not well defined.

For the extraction of EMC effect we are looking at the A/D ratios of the measured cross sections, so any A-independent scaling violations will cancel in the ratios. If the h_2 and g_2 corrections are negligible or target independent, then $F_2^{meas}(x, Q^2)$ is directly connected to $F_2^{(0)}(\xi, Q^2)$ (see Eqn 27) through a simple relation. In that case, the target mass effects on cross section ratios can be well approximated by $x \to \xi$ substitution. Our investigations show that the h_2 and g_2 terms yield corrections $\lesssim 5\%$ to the structure functions for $Q^2 > 5$ GeV^2 [100] and for E03-103, Q^2 values are greater than 5 GeV^2 for the 40 and 50 degree data above x=0.7. In the ratio, the impact is further suppressed. *WHAT ABOUT Q^2 VALUES BELOW 5 GEV^2 ($x < 0.7$)?*

Higher-twist effects can also lead to scaling violations, although it has been argued based on quark-hadron duality [101, 102] that for nuclei, the Fermi motion of the nucleons samples a sufficient kinematic region that the observed structure function reproduces the DIS limit even down to extremely low Q^2 and W^2 values [4]. This will be examined with the extensive measurements taken to examine the Q^2 dependence of the EMC ratio.

FIG. 12: Fractional quasielastic contribution to the cross section based on our model at 40 degrees for ^{2}H, ^{12}C and ^{197}Au. Here, σ_{qe} is the contribution from the quasielastic piece of the model (in the Born approximation) and σ_{Born} is the total Born cross section.

It is unclear if the extended scaling of the EMC ratio will hold true in the presence of significant contributions from quasielastic scattering [5, 102, 103]. Figure 12 shows the quasielastic contribution, $\sigma_{qe}/\sigma_{Born}$, based on our cross section model for the 40 degree kinematics. In our model, the quasielastic contribution is negligible for $x \lesssim$ 0.7, and $\lesssim$10% for all nuclei up to $x = 0.9$, with further suppression when examining target ratios.

IV. SYSTEMATIC UNCERTAINTIES

Statistical uncertainties arise from the random variation in the various yields used to compute the cross sections. The total systematic uncertainty in the cross section extraction is taken as the sum in quadrature of all systematic uncertainties of the quantities that contribute to the cross section. The components of the systematic uncertainty can be broadly divided into two groups: point-to-point uncertainties and normalization uncertainties. Point-to-point uncertainties are due to effects which may vary with time, kinematic conditions, or detector location, and so their effect is (or at least can be) uncorrelated between different data points. Normalization (scale) uncertainties affect the measurement globally (e.g., target thickness). Most corrections involve a mixture of point-to-point and normalization uncertainties. The resulting overall uncertainty in the cross section ratios is less than the total uncertainty in the cross section itself because the many of the scale uncertainties and some point-to-point type errors cancel in the ratios. Table V – summarizes the systematic uncertainties in extracting cross section ratios. The dominant remaining contributions from the scale uncertainties are those associated with the absolute target thicknesses, radiative and background corrections. These range from 1.5–2.0% on the EMC ratios, and are provided for each target ratio in the supplementary data tables [104]. Individual contributions are discussed below.

Possible offsets in the beam energy, spectrometer momentum, and spectrometer angle can yield errors in our extracted cross sections. The uncertainties associated with these quantities are determined by calculating the cross section at nominal kinematics, and comparing this to the cross section when each of the kinematic variables are shifted by the uncertainty of that variable. We use our model cross section for these studies. Note that the kinematic uncertainties almost completely cancel in the cross section ratios.

The point-to-point uncertainty in beam charge measurement was estimated to be 0.5%. This was obtained by studying the residuals of the measured currents during the calibration procedure, mainly due to small drifts of the BCM gain. A scale uncertainty of 0.2% was assumed for the charge measured, due to the UNSER calibration.

As mentioned in section II B, thicknesses of the solid targets were calculated using measurements of the mass and area of the targets. Thicknesses of the cryotargets were computed from the target density and the length of the cryogen in the path of the beam. The absolute uncertainty in the ^{2}H thickness is estimated to be 1.29%. The normalization uncertainty due to target thickness for the A/D cross section ratios are found to be 1.59% and 1.23% for the ^{3}He and ^{4}He targets respectively. For heavy nuclei, this scale uncertainty is found to be between 0.5% to 1% for the target ratios. In addition to the nominal target densities, there are corrections associated with beam heating effects and fluctuations in the pressure and temperature. The uncertainty associated with this correction comes from the uncertainties in the fits to target luminosity scans. Though no boiling correction is made in the case of the deuterium target, the uncertainty arising due to boiling of this correction are still included in A/D ratios for solid targets. We assign a scale uncertainty of $0.24\% - 0.38\%$ for the target ratios.

The scale uncertainty of the acceptance correction in the HMS was estimated to be 1% from the elastic cross section studies. This is a combination of the uncertainties from the effect of position uncertainties in the target, collimator, magnets, and detector package on the acceptance correction. The point-to-point uncertainty comes from comparison of model in the inelastic region (where the cross sections does not vary significantly) to data, and is estimated to be 1%. For the target ratios, the point-to-point uncertainty was estimated to be 0.3%. For the cryotarget ratios, the scale uncertainty was estimated to be 0.2% and for solid target ratios this is estimated to be 0.5%. This difference occurs because part of the effect cancels in the cryotarget ratios.

The normalization uncertainty of the tracking efficiency is determined to be 0.7%, mainly due to the limitations of the algorithm used for tracking. Also a point-to-point uncertainty of 0.3% is assigned to the tracking efficiency in the target ratios.

At very low x values, the structure functions are expected to scale, and any deviation is possibly due to the charge symmetric background (since this is the dominant uncertainty for heavy nuclei at small x and large scattering angles). A comparison of 40 and 50 degree data suggests that scaling is satisfied if the CSB varies by no more than 5%. A polynomial fit was made to the charge symmetric background as a function of x, and 5% of the magnitude of the charge symmetric background is applied as the point-to-point uncertainty in the charge symmetric background subtraction.

The uncertainty due to the model dependence in the radiative correction was studied by varying the DIS and QE models independently. The change in cross section was most pronounced in the low x region ($x < 0.4$). The relative uncertainty in the cross section from the model dependence is estimated to be 1%. For the helium target ratios, the point-to-point uncertainty is estimated to be 0.5% and we assign a scale uncertainty of 0.1% due to the difference in radiation length of the helium and deuterium targets. For nuclei with $A > 5$, the point-to-point uncertainty in the cross section ratios is estimated to be 0.5%. Also a scale uncertainty of 1% is assigned to the cross section ratios of nuclei with large radiation length.

The effect of the model on the bin centering corrections was studied by varying the shape of the model. This is done by supplying artificial x and Q^2 dependence as input to the individual DIS and QE pieces in the model cross section. The variation was found to be most pronounced for the $x >0.8$ region, and we estimate a point-to-point uncertainty of 0.2% for the cross sections, and 0.1% for the cross section ratios.

Uncertainties in the Coulomb corrections is mainly due to the knowledge of the energy shift, ΔE, used in the EMA calculation. We estimate this to be known at the 10% level. For the Au target at 40 degrees, this uncertainty ranged from 0.5% at low x to 1.5% at high x.

V. RESULTS AND DISCUSSION

Before presenting the results, it is instructive to compare our kinematics to the earlier SLAC experiments. This will help identify potential issues the comparison of the results and examinations of the Q^2 dependence when combining data from different experiments. Figure 13

TABLE V: Table shows the typical sources and magnitude of the systematic uncertainties in extracting cross section ratios. These are added in quadrature with the statistical uncertainties to get the total random uncertainties.

Item	Absolute uncertainty(±)	$\delta R/R$ (±%)
Beam Energy (offset)	5×10^{-4}	–
Beam Energy (tgt-dep)	2×10^{-4}	0.08
HMS Momentum (offset)	5×10^{-4}	–
HMS Momentum (tgt-dep)	2×10^{-4}	0.0-0.12
HMS angle (offset)	0.5 mrad	–
HMS angle (tgt-dep)	0.2 mrad	0.29-0.60
Beam Charge	0.5%	0.31
Target Boiling	0.45%	0.0-0.1
End-cap Subtraction	2–3%	0.28-0.45
Acceptance	1%	0.3
Tracking Efficiency	0.7%	0.3
Trigger Efficiency	0.3%	0.0
Electronic Dead Time	0.06%	0.0
Computer Dead Time	0.3%	0.3
Charge Symmetric BG		0.0-1.0
Coulomb corrections	0.2%	0.1
Pion Contamination	0.2%	0.1
Detector Efficiency	0.2%	0.0
Radiative Corrections	1%	0.5
Bin-centering	0.2%	0.1

FIG. 13: (Color online) The E03-103 kinematics, indicated with dashed and dotted lines, along with the SLAC experiments E139 [16] (triangles) and SLAC E140 [105] (squares). Kinematics are shown for the target with maximum coverage (Fe for the SLAC measurements, C for E03-103). The solid line and filled symbols represent the kinematics used in the main comparison of the results. Contours of constant invariant mass squared are also shown in the figure.

shows kinematics for our measurement and SLAC E139 and E140.

E03-103 took data on all targets at 40° and 50°, and the cross section ratios with respect to deuterium were extracted. The EMC ratios are extracted from the 40 degree angle (solid line in Fig. 13) where the data have better statistics and more complete kinematic coverage. Data were also collected for a detailed Q^2 dependency study at 8 additional kinematic settings on C and ^{2}H.

In the cross section ratio plots, representative world data is also displayed with the corresponding nuclei where available. In the kinematics comparison plot we chose to display kinematics of SLAC experiments because of the overlap in kinematics with our experiment at high x. For comparison of the EMC ratios we use the SLAC data at $Q^2 = 5$ GeV^2, except for the highest x, where $Q^2 = 10$ GeV^2. For each x, Q^2 value, published SLAC E140 results are averaged over several ϵ points and we will come back to this point latter in this section.

To be consistent, the presented SLAC data have updated Coulomb and isoscalar corrections using the same prescriptions used for the analysis of E03-103 data. The updated data points and corrections factors are available in the supplementary online material [104].

A. Q^2 dependence of the ratios

The scaling of the structure functions for nucleons is expected to hold in the conventional DIS region ($W^2 > 4$ and $Q^2 > 1$), where the non-perturbative, resonance structure is no longer apparent and only QCD evolution yields a Q^2 dependence. At smaller values of W^2, corresponding to large x, additional scaling violations can originate from resonance contributions. For E03-103, the data are in the conventional DIS region up to $x \approx 0.6$. There are indications [4] that the nuclear structure functions in the resonance region, down to very low W^2 values ($W^2 > 1.5$ GeV^2 for $Q^2 > 3$ GeV^2), shows the same global behavior as in the DIS region. Therefore, we took data at large x extending below $W^2 = 4$ GeV^2, and made detailed measurements of the Q^2 dependence of the ratios to ensure that there was no indication of any systematic deviation from the DIS limit.

The EMC ratios for carbon at several Q^2 values are compared in Fig. 14. The top panel shows the EMC ratios for the five highest Q^2 settings from our experiment, along with our new parametrization for the EMC effect (see section V D). The data do not show any systematic Q^2 dependence, and the scatter at the largest x values is consistent with the uncertainties in the individual measurements. This suggests that any Q^2 dependence in the structure function is either small or cancels in the target ratios. The bottom figure shows the low Q^2 measure-

FIG. 14: Ratio of C and ^{2}H cross sections for the five largest Q^2 (top panel) and five lowest Q^2 (bottom panel) settings as a function of x. Uncertainties are the combined statistical and point-to-point systematic. The Q^2 values quoted are for $x = 0.75$, and the data labeled Q^2=5.33 correspond to our primary results, taken at 40°.

FIG. 15: EMC ratios for the C data (top) and the Cu and Fe data (bottom) as a function of Q^2 at fixed x values as indicated in legend. For clarity, an additive offset is applied along the y axis. Open symbols are from updated SLAC E139 [16] results while the closed symbols are E03-103 values. Inner error bars shows the combined statistical and point-to-point systematic while the outer error bars represents the total uncertainty including the normalization uncertainties.

ments, where there is a clear difference in the Q^2 dependence of carbon and deuterium below $Q^2 \approx 3$ GeV^2 and $x > 0.6$, corresponding to W^2 values below 2–3 GeV^2, where one expects large resonance contributions.

Figure 15 shows the Q^2 dependence of the structure functions for C (top) and Cu or Fe (bottom) at several x values, to allow for a more careful examination of the Q^2 dependence as a function of x. The carbon data have additional Q^2 values for E03-103, due to the data taken using a lower beam energy, while the Cu data have more high-Q^2 data from the SLAC measurements. There is a fair agreement with the SLAC data over the kinematic regions where data are available, and clear deviations from a constant ratio are visible below $Q^2 = 4$ GeV^2 and large x values.

B. x dependence of the ratios

Need to summarized differences from PRL values (e.g. isoscalar correction) and errors (added CC error).

We now examine the x dependence of the EMC ratios for all of the targets from E03-103 and SLAC, including Coulomb corrections and our updated isoscalar corrections. We first discuss the cross section ratios for C and ^{4}He, as these ratios have no isoscalar correction, and the Coulomb distortion effects are small (<1%) for these nuclei. Figure 16 shows the cross section ratios for ^{4}He and ^{12}C, along with the updated SLAC E139 data and the NMC data [18, 19]. There is a good agreement between the data sets, but the E03-103 result is of high precision at large x, although it is at a lower W^2 than previous measurements.

Figure 17 shows the cross section ratios for ^{3}He and ^{9}Be. Both of these nuclei are light enough that the Coulomb corrections are small, but required a proton (neutron) excess correction to obtain the isoscalar EMC ratios (see section III J). The magnitude of this correction is significant for ^{3}He, ranging from about 5% to 15% for our kinematics. For ^{9}Be, the correction is of the opposite sign and roughly a factor of three smaller. The ^{3}He EMC ratios exhibit the general shape observed for the cross section ratios for heavy nuclei.

FIG. 16: EMC ratios for ^{4}He and ^{12}C as a function of x for the 40 degree data. Uncertainties are the combined statistical and point-to-point systematic. Normalization uncertainties are shown in the parenthesis. Also shown are the updated SLAC E139 [16] and NMC data [18, 19]. The solid curves show our A dependent parametrization for the EMC effect. *NMC data is as-published, not updated. Is the fit OURS or the SLAC fit? Mention differences in error bar in text?*

FIG. 17: Isoscalar EMC ratios for ^{3}He and ^{9}Be for the 40 degree data. Uncertainties are the combined statistical and point-to-point systematic and normalization uncertainties are shown in the parenthesis. Also shown are the HERMES data [20, 21] (updated to include our modified isoscalar correction). The solid curve shows an A dependent parametrization for the EMC effect in ^{3}He.

One can avoid the uncertainty associated with the isoscalar correction, and thus better evaluate models of the EMC effect, by taking the ratio of ^{3}He to (^{2}H+^{1}H) which allows comparisons to calculations that are independent of the neutron structure function. These ratios are extracted for our 40 degree setting and shown in Figure 17 (squares). *WRONG FIGURE!* The isoscalar-corrected ^{3}He/^{2}H ratio and the ^{3}He/(^{2}H+^{1}H) results are in good agreement below $x \approx 0.65$, but the resonance structure at large x in the proton is not washed out, and so the extended scaling observed in nuclei [4] is not as effective, limiting the useful range for this ratio to $x \lesssim 0.65$.

Next, we show the ratios for heavy nuclei in Fig. 18. Several corrections to the data on heavy nuclei are larger or more uncertain than for light nuclei. At low x, the radiative corrections and charge symmetric background (see section III C 2) are quite large. At high x, Coulomb distortion becomes large for high-Z targets; the correction for Au ranges from 3% at low x to 12% at high x values for the 40° data.

Taking normalization uncertainties into account, our large-x results are in generally good agreement with the SLAC data, although the SLAC ratios at $x = 0.8$ are always higher than our results. This is because the $x = 0.8$ points for SLAC are taken at higher Q^2 values ($Q^2 = 10$ GeV^2), leading to a noticeable difference between the target mass corrections needed for the two experiments. Figure 19 shows the points plotted as a function of x (left panels) and ξ (right panels), where plotting the ratio vs. ξ provides the dominant part of the target mass correction. While all of the points shift to lower values of ξ, the effect is most significant at large x, where the shift is larger. When plotted as a function of ξ, the EMC ratios are consistent.

NF: Should we be taking slopes vs ξ? JRA: May be good idea, as it will reduce potential difference for points with only SLAC or JLab measurements. Since we're the only ones using slope, there's no conflict with long-used fits vs x.

At small x values, we find systematic disagreements with the SLAC measurements. While the light isoscalar

FIG. 18: EMC ratios for Fe and Cu (top) and for Au (bottom) as a function of x for the 40 degree data. Uncertainties are the combined statistical and point-to-point systematic. Normalization uncertainties are shown in the parenthesis. The SLAC E139 and E140 data include updated Coulomb and isoscalar corrections. BCDMS [106] Fe data are shown as published.

nuclei are in relatively good agreement with the E139 results, the ^{3}He ratios are systematically higher than SLAC for $x \leq 0.4$, and the very heavy nuclei are systematically higher. Given the normalization uncertainties, it is difficult to conclude that there is a true inconsistency between the data sets, but we examine the pattern of disagreement to evaluate possible explanations for the small differences.

First, note that these nuclei have large isoscalar corrections, which are of the opposite sign for ^{3}He and the heavy nuclei. However, the low-x region has the least uncertainty in the ratio of F_2^n/F_2^p [56, 57], and the correction becomes smaller at low-x values, where the F_2^n/F_2^p becomes closer to unity. In addition, the SLAC data as presented here include the updated isoscalar correction that we apply to our data, and thus such a discrepancy would have to be associated with the Q^2 dependence of the isoscalar correction. It thus seems unlikely that it could be responsible for the difference between data sets at small x.

The heavy nuclei also have significant corrections due to Coulomb distortion, radiative corrections, and charge-

FIG. 19: EMC ratios for our Cu (top) and Au (bottom) data compared to the SLAC Fe and Au data, respectively, shown using four different sets of corrections. The panels on the left (right) side show the ratio vs x (ξ), while the panels on the top (bottom) show the ratios with (without) Coulomb corrections applied. For each target, the top-right figure is the version where one expects the best agreement between different measurements, assuming that the Coulomb and target mass corrections account for any θ and Q^2 dependence in the cross section ratios. For all nuclei, high-x SLAC and JLab results are in good agreement, after taking into account the scale uncertainties in the measurements.

symmetric backgrounds. However, the Coulomb corrections are smaller at low x, and the charge-symmetric background is directly measured for all nuclei. In addition, errors in any of these corrections would not naturally be expected to yield corrections of the opposite sign for ^{3}He and the heaviest nuclei.

As noted in Sec. I A and Ref. [107], if $R = \sigma_L/\sigma_T$ depends on A, then the cross section ratio we show here will not be identical to the ratio of the F_2 structure functions. There have been some indications of possible A dependence to R [108–111]. These suggestions are consistent with a decrease(??) in R for nuclei with more neutrons, which could explain the observation of an increase in σ_A/σ_D for ^{3}He and a decrease for heavier nuclei with a significant neutron excess. However, we cannot exclude the possibility that these features are the result of errors in our knowledge of the thickness of these targets which give shifts in the ratios which happen to vary with the N/Z ratio of the nucleus.

C. A dependence of the ratios

Table V C shows the EMC slopes extracted from data from the SLAC experiment and this experiment. This table is an updated version of table 1 provided in [22] which includes some of the updated results from E03-103. These slopes are shown vs A in Fig. **??**. STATEMENT ON CONSISTENCY, IMPROVED PRECISION, NEW NUCLEI. Our light nuclei results, in particular for ^{9}Be, show a clear deviation from scaling with density [50], while the lightest nuclei show deviations from a smooth scaling with A. It has been suggested that the local density or the overlap of the struck nucleon with nearby neighbors may drive the scaling of the EMC effect [22, 50**?**], or that off-shell effects in the highly virtual nucleons may in fact be responsible [112]. In connection with these ideas, it has been suggested that there may be both an A dependence and an isospin dependence, with additional modification in neutron-rich nuclei [22, 34, 113]. This will be discussed in the following section.

TABLE VI: Combined EMC slopes, $|dR_{EMC}/dx|$, extracted from SLAC [16, 22] and this experiment. *JRA: THE SLAC NUMBERS ARE IDENTICAL TO THE EMC/SRC PAPER; SHOULDN'T THEY HAVE THE UPDATED ISOSCALAR AND COULOMB CORRECTIONS? SMALL BUT WORTH INCLUDING SO THAT ALL OF OUR SLAC RESULTS ARE THE UPDATED VERSIONS.*

A	JLAB E03-103	SLAC E139	Combined
^{3}He	0.087 ± 0.028	-	0.087 ± 0.028
^{4}He	0.198 ± 0.027	0.191 ± 0.061	0.197 ± 0.025
Be	0.267 ± 0.030	0.208 ± 0.038	0.245 ± 0.023
C	0.280 ± 0.029	0.318 ± 0.041	0.292 ± 0.024
Al	-	0.325 ± 0.034	0.325 ± 0.034
^{40}Ca	-	0.350 ± 0.047	0.350 ± 0.047
Fe	-	0.388 ± 0.032	0.388 ± 0.032
Cu	0.408 ± 0.037	-	0.408 ± 0.037
Ag	-	0.496 ± 0.051	0.496 ± 0.051
Au	0.484 ± 0.???	0.409 ± 0.039	0.436 ± 0.031

FIG. 20: EMC slope vs. A for SLAC E139 and JLab E03-103.

D. Modified parametrization of the EMC effect

UPDATED PARAMETERIZATION?? Want to make sure it doesn't have pathologies at low/high x if we want to suggest it as an improvement.

Though the parametrization of the EMC effect provided by SLAC analysis [16] globally describes the presented data, it is clear [22, 50] that the EMC effect cannot be explained by a simple ad-hoc logarithmic A-dependence or in terms of the average nuclear density. Results from the light nuclei suggests that the nuclear modification may depends on clustering effects and is mainly driven by the local environment of the nuclei under examination. This motivated us to do a detailed investigation of the modified parametrization for the EMC effect.

For the parametrization, we make use of the fact that the measurements show a universal shape and a weak dependence on A. The data can be parameterized as $\sigma^A/\sigma^D = 1.0 + f(x)\ |dR^A_{EMC}/dx|$, where σ^A/σ^D is the isoscalar corrected EMC ratios and $|dR^A_{EMC}/dx|$ is the absolute value of the EMC slope for the corresponding nuclei. As explained in [50], the magnitude of the EMC effect is defined as the value of the slope of a linear fit, dR_{EMC}/dx, to the cross section ratios for $0.35 < x < 0.7$. Here, f(x) is polynomial fit done to the available world data for carbon to get the shape (x dependence) of the EMC effect and is given by $f(x) = -0.28243 + 6.9324x -$

$40.886x^2 + 103.01x^3 - 125.77x^4 + 59.399x^5$. In this way a simple connection can be made to the observed effect and the EMC slopes extracted for the corresponding nuclei. These parametrization also describes the trends observed in NMC [18, 19], SLAC[16] data and are only valid in the region $0.01 < x < 0.95$.

Though the resulting parametrization still depends on the mass number via the slope and doesn't have the local properties or the details of the clustering effects of the corresponding nuclei, it gives a better description of the trends in the observed nuclear dependence. The A-dependent curves presented here are plotted with extracted values of the combined EMC slopes as given in Table V C. However, for arbitrary nuclei, the EMC slopes can be obtained from a linear fit to the mass dependence. Figure 21 shows the $\mathrm{A}^{-1/3}$ dependence of the extracted slopes. Also shown is a linear fit (solid lines) for A≥12. The fit is limited up to A=12 and is based on the assumption that the nuclear density distributions have a common shape and that for these medium-heavy nuclei, the nuclear effects scale as a linear function of $\mathrm{A}^{-1/3}$ [22, 114]. However, as one can see from the figure, the functional form 0.5530 - 0.6141 $\mathrm{A}^{-1/3}$ gives a fairly reasonable description of the magnitude of the EMC slopes observed even in the light nuclei (dashed lines).

FIG. 21: Magnitude of the extracted EMC slopes vs. $\mathrm{A}^{-1/3}$. Here, the solid lines shows the fit for nuclei with A≥12, while the dashed line shows the trend in $\mathrm{A}^{-1/3}$ obtained from such a linear fit for the light nuclei.

FIG. 22: EMC vs SRC stuff. Need to update Niso/Ntot correction.

E. SRC-EMC discussion

updated SRC-EMC plot with E03-103 heavy nuclei. Need plots with updated Ntot/Niso for LD, need chisquared values for LD fits without the CM motion uncertainty for comparison. Ntot/Niso shifts heavier nuclei to the right, improving linear correlation. In both cases, still see some residual excess in Fe, Cu, Au (but not very significant in LD case).

While there have been many theoretical models put forth as explanations for the EMC effect during the last 30 years, a recent experimental observation has emerged as a tantalizing possibility. A suggestive correlation has been established between the "insert synonym for EMC effect" and a_2 or R_{2N}, the quantities connected to the relative number of high momentum nuclei or short-range correlations relative to the deuteron [22, 34, 112]. The two quantities are connected by a center-of-mass motion correction that needs to be applied to the raw a_2 ratio,

TABLE VII:

TEST	χ^2/NDF	slope	intercept
HV-0	1.47	0.0893	N/A
HV-2	1.44	0.0906	-0.0044
HV-D	1.26	0.1067	-0.0582
LD-0	0.57	0.0520	N/A
LD-2	0.64	0.0541	-0.0124
LD-D	0.57	0.0522	0.011

FIG. 23: EMC vs SRC stuff. Need to update Niso/Ntot correction.

which comes from A/D high momentum tails to account for the fact that the deuteron-like pair in the A nucleus is free to move around in the field of the other nucleons. There have been two explanations offered for the linear relationship seen between the SRC results and the EMC results. The first [112] suggests that it's the virtuality that's responsible for the nuclear dependence of both quantities and a simple linear fit between dR_{EMC}/dx and a_2 tests that hypothesis. The second idea [22] links the size of the EMC effect directly to the number of high-density nucleon configurations, as the early data suggested [50], specifically, NN pairs. As was established at Jlab [63] and BNL [115], the short-range correlation pairs are overwhelmingly np, so to make a connection to all NN pairs, we need to scale R_{2N} by $A(A-1)/2)/NZ$ before doing our linear test. Several different variations of this test were performed and are described in detail in Ref. [22]. However, the data does not conclusively favor one explanation over the other. We repeat the comparisons here, with new results on heavy nuclei for the EMC effect, as well as updated results for the light nuclei. The results are summarized in Table. VII and the fit using a deuteron constraint is shown in Fig. 24.

The results have not changed very much from what was presented in [22], as far as the EMC effect for the deuteron (zero by definition), or the IMC effect in the deuteron (deviation from the sum of neutron and proton structure functions). However, the "goodness" of the fits did move - with chi^2 improving for all the LD scenarios and getting worse for the HV scenarios. The extreme was for the case of the constrained deuteron fit (using a deuteron point with errors to account for correlations between the other points), with chi^2 of 10 and 4 for the LD and HV hypotheses, respectively.

However, on the whole, the situation remains largely unchanged - with the need for more data as urgent as ever.

VI. CONCLUSIONS

Deep inelastic scattering from ^{1,2}H, ^{3,4}He, Be, C, Cu, and Au solid targets was measured by the E03-103 experiment at the Jefferson Lab. The ratios of inclusive nuclear cross sections with respect to the deuterium cross section have been determined for $x > 0.3$ for Q^2 values between 3 and 8 GeV^2.

no sign of modified x-dependence for light nuclei, but clear deviations from commonly assumed A and rho dependence.

E03-103 experiment addressed some of the limitations in previous measurements of the EMC effect. The measurement provided benchmark data for calculations of the EMC effect in light nuclei. No deviations from the x dependence observed in heavy nuclei was found for $A = 3, 4$, but clear deviations from the simple assumption of mass or density scaling of the EMC effect are seen. At large x, where binding and Fermi motion effects dominate, our new data for light and heavy nuclei can serve as a base-line for traditional nuclear physics calculations, including several few-body nuclei where structure related uncertainties are minimal. The data presented in this work will bridge the gap between measurement of the EMC effect in light nuclei and medium heavy nuclei, thus providing a comprehensive basis to test state of the art models that attempt to explain the observed nuclear dependence. For the moment, few models provide an explicit prediction for the A dependence, thus limiting the ability to directly constrain these models without further effort on the theory side.

While these data provide important new information about the EMC effect, there are still limitations on how well these results could be used to constrain explanations of the EMC effect. Some of these limitations will be addressed by the 12 GeV experiment at Jefferson Lab [116]. This will provide further information on the detailed behavior of the observed nuclear nuclear dependence with an expanded set of light nuclei, including nuclei with significant cluster structure.

OTHER 12 GeV experiments: off-shell DIS, off-shell FFs, EMC/SRC for 3H/3He, 40Ca/48Ca, A-dep of R, etc...

FIG. 24: Tests of the high virtuality (HV) and local density (LD) hypotheses for the relationship between the A/D structure function ratios and SRC ratios. The black line indicates a 2-parameter fit with no constraints and the red dotted line is a fit with a string deuteron constraint (intercept required to be zero).

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