Measurement of the $F_n^2/F_p^2$ and d/u Ratios in Deep Inelastic Electron Scattering off $^3$H and $^3$He

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ABSTRACT

We discuss a possible measurement of the ratio of the nucleon structure functions, $F_n^2/F_p^2$, and the ratio of up to down quark distributions, $u/d$, at large $x$, by performing deep inelastic electron scattering from the $^3$H and $^3$He mirror nuclei with the 11 GeV upgraded beam of Jefferson Lab. The measurement is expected to be almost free of nuclear effects, which introduce a significant uncertainty in the extraction of these two ratios from deep inelastic scattering off the proton and deuteron. The results are expected to test perturbative and non-perturbative mechanisms of spin-flavor symmetry breaking in the nucleon, and constrain the structure function parametrizations needed for the interpretation of high energy $e$-$p$, $p$-$p$ and $p$-$\bar{p}$ collider data. The precision of the expected data can also allow for testing competing parametrizations of the nuclear EMC effect and provide valuable constraints on models of its dynamical origin.

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1 Introduction
Measurements of the proton and deuteron structure functions have been of fundamental importance in establishing the internal quark structure of the nucleon [1]. The first evidence for the presence of point-like constituents (partons) in the nucleon came from the observation that the ratio of inelastic to Mott cross sections, measured in the pioneering SLAC experiments, exhibited only small variation with momentum transfer [2]. The subsequent detailed analysis of the SLAC data [3] revealed the predicted “scaling pattern” [4] in the nucleon structure functions, consistent with scattering from partons carrying the quantum numbers of the Gell-Mann/Zweig quarks. Further experimental studies of muon-nucleon and neutrino-nucleon deep inelastic scattering experiments at CERN and Fermilab established beyond any doubt the quark-parton model (QPM) of the nucleon [5], and provided substantial supporting evidence for the emerging theory of quantum chromodynamics (QCD).

The cross section for inelastic electron-nucleon scattering is given in terms of the structure functions \( F_1(\nu, Q^2) \) and \( F_2(\nu, Q^2) \) of the nucleon by:

\[
\sigma \equiv \frac{d^2\sigma}{d\Omega dE'}(E, E', \theta) = \frac{4\alpha^2(E')^2}{Q^4} \cos^2\left(\frac{\theta}{2}\right) \left[ \frac{F_2(\nu, Q^2)}{\nu} + \frac{2F_1(\nu, Q^2)}{M} \tan^2\left(\frac{\theta}{2}\right) \right],
\]

where \( \alpha \) is the fine-structure constant, \( E \) is the incident electron energy, \( E' \) and \( \theta \) are the scattered electron energy and angle, \( \nu = E - E' \) is the energy transfer, \( Q^2 = 4EE'\sin^2(\theta/2) \) is minus the four-momentum transfer squared, and \( M \) is the nucleon mass.

The basic idea of the quark-parton model [4, 6] is to represent inelastic electron-nucleon scattering as quasi-free scattering from the partons/quarks in the nucleon, when viewed in a frame where the nucleon has infinite momentum (the center-of-mass frame is a very good approximation to such a frame). The fractional momentum of the nucleon carried by the struck quark is given by the Bjorken scaling variable, \( x = Q^2/2M\nu \). In the limit where \( \nu \to \infty, Q^2 \to \infty \) with \( x \) fixed, the nucleon structure functions become:

\[
F_1 = \frac{1}{2} \sum_i e_i^2 f_i(x), \quad F_2 = x \sum_i e_i^2 f_i(x).
\]

Here, \( e_i \) is the fractional charge of quark type \( i \), \( f_i(x)dx \) is the probability that a quark of type \( i \) carries momentum in the range between \( x \) and \( x + dx \), and the sum runs over all quark types.

Since the charges of the \( u, d \) and \( s \) quarks are \( 2/3 \), \(-1/3 \) and \(-1/3 \), respectively, the \( F_2(x) \) structure function for the proton is given by:

\[
F_2^p(x) = x \left[ \left(\frac{2}{3}\right)^2 (u + \bar{u}) + \left(-\frac{1}{3}\right)^2 (d + \bar{d}) + \left(-\frac{1}{3}\right)^2 (s + \bar{s}) \right].
\]

The structure function of the neutron is related to that of the proton by isospin symmetry. Since the up/down quarks and proton/neutron both form isospin doublets one has: \( u^p(x) = \ldots \)
\[ d^n(x) \equiv u(x), \ d^p(x) = u^n(x) \equiv d(x), \ s^n(x) = s^p(x) \equiv s(x) \] (with analogous relations for the antiquarks), and:

\[
F_n^2(x) = x \left[ \left(-\frac{1}{3}\right)^2 (u + \bar{u}) + \left(\frac{2}{3}\right)^2 (d + \bar{d}) + \left(-\frac{1}{3}\right)^2 (s + \bar{s}) \right]. \quad (4)
\]

Equations 3 and 4 result in the structure function ratio:

\[
\frac{F_n^2}{F_p^2} = \frac{(u + \bar{u}) + (s + \bar{s}) + 4(d + \bar{d})}{4(u + \bar{u}) + (d + \bar{d}) + (s + \bar{s})}. \quad (5)
\]

Since all the distribution functions must be positive for all \(x\), the above expression is bound for all \(x\) by:

\[
\frac{1}{4} \leq \frac{F_n^2}{F_p^2} \leq 4, \quad (6)
\]

which is known as the Nachtmann inequality \[7\]. Figure 1 (left) shows all the SLAC deep inelastic scattering (DIS) (large \(Q^2\) and \(\nu\)) data from the pioneering SLAC/MIT Collaboration experiments on the \(F_n^2/F_p^2\) ratio versus \(x\). The ratio has been extracted from DIS measurements off the proton and deuteron \[8\], using a non-relativistic smearing model to account for the Fermi-motion of the nucleons in the deuteron \[9\]. The ratio data are within the bounds of the Nachtmann inequality. For large \(x\), the ratio is about 1/4 which can only be reached if \(d = \bar{d} = s = \bar{s} = 0\). This suggests a picture in which the high momentum partons in the proton (neutron) are mainly up (down) quarks. For small \(x\) the ratio is close to 1, suggesting little influence of valence quarks and dominance of the quark-antiquark “sea”.

### 2 Theory Overview

The \(F_n^2/F_p^2\) ratio can be calculated in a number of models of the nucleon. In a world of exact SU(6) symmetry, the wave function of a proton, polarized in the +\(z\) direction for instance, would be simply \[5\]:

\[
p^\uparrow = \frac{1}{\sqrt{2}} u^\uparrow (ud)_{S=0} + \frac{1}{\sqrt{18}} u^\uparrow (ud)_{S=1} - \frac{1}{3} u^\downarrow (ud)_{S=1}
\]

\[
- \frac{1}{3} d^\uparrow (uu)_{S=1} - \frac{\sqrt{2}}{3} d^\downarrow (uu)_{S=1}, \quad (7)
\]

where the subscript \(S\) denotes the total spin of the “diquark” partner of the quark. In deep-inelastic scattering, exact SU(6) symmetry would be manifested in equivalent shapes for the valence quark distributions of the proton, which would be related simply by \(u_\nu(x) = 2d_\nu(x)\) for all \(x\). For the neutron to proton structure function ratio this would imply \[10\]:

\[
\frac{F_n^2}{F_p^2} = \frac{2}{3}, \quad \frac{u}{d} = \frac{1}{2} \quad [SU(6) \text{ symmetry}]. \quad (8)
\]
In nature, spin-flavor SU(6) symmetry is, of course, broken. The nucleon and Δ masses are split by some 300 MeV. In deep inelastic scattering off the nucleon, this symmetry breaking is reflected in the experimental observation that the $d$ quark distribution is softer than the $u$ quark distribution, with the $F_{2n}^2/F_{2p}^2$ ratio deviating from the SU(6) expectation. The correlation between the mass splitting in the 56 baryons and the large-$x$ behavior of $F_{2n}^2/F_{2p}^2$ was observed some time ago by Close [11] and Carlitz [12]. Based on phenomenological [11] and Regge [12] considerations, and kinematic arguments by Close and Thomas [13], the breaking of the symmetry in Equation 7 was argued to arise from a suppression of the “diquark” configurations having $S = 1$ relative to the $S = 0$ configuration as $x \to 1$. From Equation 7, a dominant scalar valence diquark component of the proton suggests that in the $x \to 1$ limit, $F_{2p}^2$ is essentially given by a single quark distribution (i.e. the $u$), in which case:

$$\frac{F_{2n}^2}{F_{2p}^2} \to \frac{1}{4}, \quad \frac{d}{u} \to 0 \quad [S = 0 \text{ dominance}].$$

(9)

This expectation has, in fact, been built into most phenomenological fits to the parton distribution data [14].
The phenomenological suppression of the $d$ quark distribution at intermediate and large $x$ can be understood in terms of the same hyperfine interaction responsible for the $N - \Delta$ splitting [13, 15, 16]. This color hyperfine interaction is generated by one-gluon exchange between quarks in the core [15]. At lowest order, the Hamiltonian for the color-magnetic hyperfine interaction [15] between two quarks is proportional to $\vec{S}_i \cdot \vec{S}_j$, where $\vec{S}_i$ is the spin vector of quark $i$. Because this force is repulsive if the spins of the quarks are parallel and attractive if they are antiparallel, Isgur [16] argued that the SU(6) wave function in Equation 7 naturally leads to an increase in the mass of the $\Delta$ and a lowering of the mass of the nucleon, and a softening of the $d$ quark distribution relative to the $u$.

An alternative suggestion, based on a perturbative QCD argument, was originally formulated by Farrar and Jackson [17]. Their proposal might be expected to hold at very large $x$, where the struck quark has momentum approaching infinity, which goes beyond mean field theory (like the simple quark model). They showed that the exchange of longitudinal gluons, which are the only type permitted when the spins of the two quarks in $(qq)_S$ are aligned, would introduce a factor $(1 - x)^{1/2}$ into the Compton amplitude – in comparison with the exchange of a transverse gluon between quarks with spins anti-aligned. In this approach the relevant component of the proton valence wave function at large $x$ is that associated with states in which the total “diquark” spin projection, $S_z$, is zero as $x \rightarrow 1$. Consequently, scattering from a quark polarized in the opposite direction to the proton polarization is suppressed by a factor $(1 - x)$ relative to the helicity-aligned configuration.

A similar result is also obtained in the treatment of Brodsky et al. [18] (based on quark-counting rules), where the large-$x$ behavior of the parton distribution for a quark polarized parallel ($\Delta S_z = 1$) or antiparallel ($\Delta S_z = 0$) to the proton helicity is given by: $q_{i\uparrow\downarrow}^* (x) = (1 - x)^{2n-1+\Delta S_z}$, where $n$ is the minimum number of non-interacting quarks (equal to 2 for the valence quark distributions). Using Equation 7 in the $x \rightarrow 1$ limit one therefore predicts:

$$\frac{F_n^2}{F_p^2} \rightarrow \frac{3}{7}, \quad \frac{d}{u} \rightarrow \frac{1}{5} \quad [S_z = 0 \text{ dominance}].$$

It should be noted that in the latter two treatments, the $d/u$ ratio does not vanish and the $F_n^2/F_p^2$ ratio is 3/7 instead of 1/4.

### 3 Motivation for a New Experiment

Although the problem of extracting neutron structure functions from deuteron data is rather old [19], the discussion has been recently revived [20, 21] with the realization [22] that $F_n^2$, extracted from $F_d^2$ by taking into account Fermi-motion and binding effects, could be significantly larger [20, 21, 22] than that extracted in earlier analyses [9] in which only Fermi-motion corrections were applied.

Melnitchouk and Thomas [20] have incorporated binding and off-shell effects within a covariant framework in terms of relativistic deuteron wave functions (as calculated by Gross
and collaborators [23], for instance). Neglecting the relativistic deuteron 
$P$-states and off-shell deformation of the bound nucleon structure function 
(which were found to contribute at the $\sim 1\%$ level [20]), the deuteron 
structure function, $F_2^d$, can be written as a convolution of the free 
proton and neutron $F_2$ structure functions and a nucleon momentum 
distribution in the deuteron, $f_{N/d}$:

$$F_2^d(x, Q^2) = \int dy f_{N/d}(y) \left[ F_2^p(x/y, Q^2) + F_2^n(x/y, Q^2) \right], \quad (11)$$

where $y$ is the fraction of the ‘plus’-component of the nuclear momentum 
carried by the interacting nucleon, and $f_{N/d}(y)$ takes into account both Fermi-motion and binding effects. Their calculation results in larger $F_2^n/F_2^p$ values compared with the Fermi-motion only extracted values. As can be seen in Figure 1 (right), the difference at $x = 0.85$ can be up to $\sim 50\%$.

Whitlow et al. [22] incorporated binding effects by estimating the EMC effect [24, 25] of the deuteron itself (difference between the free and bound nucleon quark distributions) using the “nuclear density model” of Frankfurt and Strikman [26]. In this model, the EMC effect for the deuteron scales with nuclear density as for heavy nuclei:

$$\frac{F_2^d}{F_2^p + F_2^n} = 1 + \frac{\rho_d}{\rho_A - \rho_d} \left[ \frac{F_2^A}{F_2^d} - 1 \right], \quad (12)$$

where $\rho_d$ is the deuteron charge density, and $\rho_A$ and $F_2^A$ refer to a heavy nucleus with mass number $A$. This model predicts $F_2^n/F_2^p$ values that are significantly higher ($> 100\%$) than the Fermi-motion only extracted ones at high $x$, as can be seen in Fig. 1 (right).

It is evident from the above two models that neglecting nuclear binding effects in the deuteron can introduce, at large $x$, a significant uncertainty in the extraction of $F_2^n/F_2^p$ and $d/u$. In the absence of experimental data or a unique theory for the magnitude of binding effects and the existence of the EMC effect in the deuteron, the question of the large-$x$ behavior of $F_2^n/F_2^p$ and $d/u$ can only be settled by a measurement which does not rely on the use of the deuteron as an effective neutron target.

The above situation can be remedied by using a method proposed by Afnan et al. [27], which maximally exploits the mirror symmetry of $A = 3$ nuclei and extracts the $F_2^n/F_2^p$ ratio from DIS measurements off $^3$H and $^3$He. Regardless of the absolute values of the nuclear EMC effects in $^3$He or $^3$H, the differences between these will be small – on the scale of charge symmetry breaking in the nucleus – which allows a determination of the $F_2^n/F_2^p$ and $d/u$ ratios at large-$x$ values essentially free of nuclear contamination.

4 Exploring Deep Inelastic Scattering off $^3$H and $^3$He

In the absence of a Coulomb interaction and in an isospin symmetric world, the properties of a proton (neutron) bound in the $^3$He nucleus would be identical to that of a neutron (proton) bound in the $^3$H nucleus. If, in addition, the proton and neutron distributions in $^3$He (and
in $^3$H) were identical, the neutron structure function could be extracted with no nuclear corrections, regardless of the size of the EMC effect in $^3$He or $^3$H separately. In practice, $^3$He and $^3$H are of course not perfect mirror nuclei – their binding energies for instance differ by some 10% – and the proton and neutron distributions are not quite identical. However, the $A = 3$ system has been studied for many years, and modern realistic $A = 3$ wave functions are known to rather good accuracy.

Defining the EMC-type ratios for the $F_2$ structure functions of $^3$He and $^3$H (weighted by corresponding isospin factors) by:

$$R(\text{He}) = \frac{F_2^{^3\text{He}}}{2F_2^p + F_2^n}, \quad R(\text{H}) = \frac{F_2^{^3\text{H}}}{F_2^p + 2F_2^n},$$

(13)

one can write the ratio of these as $R^* = R(\text{He})/R(\text{H})$, which directly yields the ratio of the free neutron to proton structure functions:

$$\frac{F_2^n}{F_2^p} = \frac{2R^* - F_2^{^3\text{He}}/F_2^{^3\text{H}}}{2F_2^{^3\text{He}}/F_2^{^3\text{H}} - R^*}.$$  

(14)

The $F_2^n/F_2^p$ ratio extracted via Equation 14 does not depend on the size of the EMC effect in $^3$He or $^3$H, but rather on the ratio of the EMC effects in $^3$He and $^3$H. If the neutron and proton distributions in the $A = 3$ nuclei are not dramatically different, one might expect $R^* \approx 1$. To test whether this is indeed the case requires an explicit calculation of the EMC effect in the $A = 3$ system.

The conventional approach employed in calculating nuclear structure functions in the valence quark region is the impulse approximation, in which the virtual photon, $\gamma^*$, scatters incoherently from individual nucleons in the nucleus [28]. The nuclear cross section is determined by factorizing the $\gamma^*$–nucleus interaction into $\gamma^*$–nucleon and nucleon–nucleus amplitudes. The structure function of a nucleus, $F_2^A$, can then be calculated by folding the nucleon structure function, $F_2^N$, with the nucleon momentum distribution in the nucleus, $f_{N/A}$:

$$F_2^A(x) = \int dy f_{N/A}(y) F_2^N(x/y) \equiv f_{N/A}(x) \otimes F_2^N(x),$$

(15)

where the $Q^2$ dependence in the structure functions is implicit. The convolution expression in Equation 15 is correct in the limit of large $Q^2$; at finite $Q^2$ there are additional contributions to $F_2^A$ from the nucleon $F_2^N$ structure functions, although these are suppressed by powers of $M^2/Q^2$, where $M$ is the nucleon mass.

The distribution $f(y)$ of nucleons in the nucleus is related to the nucleon spectral function $S(p)$ by [28]:

$$f(y) = \int d^3\vec{p} \left(1 + \frac{p_z}{p_0}\right) \delta \left(y - \frac{p_0 + p_z}{M}\right) S(p),$$

(16)

where $p$ is the momentum of the bound nucleon. For an $A = 3$ nucleus, $S(p)$ is evaluated from the three-body nuclear wave function, calculated by either solving the homogeneous Faddeev
equation with a given two-body interaction \[27, 29\] or by using a variational technique \[30\]. Details of the computation of the wave functions can be found in Ref. \[29\].

In terms of the proton and neutron momentum distributions, the \( F_2 \) structure function for \(^3\)He is given by:

\[
F_2^{3\text{He}} = 2f_{p/3\text{He}} \otimes F_2^p + f_{n/3\text{He}} \otimes F_2^n.
\]

Similarly for \(^3\)H, the structure function is evaluated from the proton and neutron momentum distributions in \(^3\)H:

\[
F_2^{3\text{H}} = f_{p/3\text{H}} \otimes F_2^p + 2f_{n/3\text{H}} \otimes F_2^n.
\]

Because isospin symmetry breaking effects in nuclei are quite small, one can to a good approximation relate the proton and neutron distributions in \(^3\)He to those in \(^3\)H:

\[
f_{n/3\text{H}} \approx f_{p/3\text{He}}, \quad f_{p/3\text{H}} \approx f_{n/3\text{He}},
\]

although in practice one has to consider both the isospin symmetric and isospin symmetry breaking cases explicitly.

The ratio \( R^* \) of EMC ratios for \(^3\)He and \(^3\)H, as calculated by Afnan et al. \[27\] is shown in Figure 2 (left) for nuclear model wave functions based on a) the “Paris (EST)” separable approximation \[31\] to the Paris potential, b) the unitary pole approximation \[32\] of the Reid Soft Core (RSC) potential, and c) the Yamaguchi potential with 7% mixing between \(^3S_1\) and \(^3D_1\) waves \[33\]. In all three cases, the CTEQ parameterization \[14\] of parton distributions at \( Q^2 = 10 \) (GeV/c)^2 was used for \( F_N^X \). The EMC effects are seen to largely cancel over a large range of \( x \), out to \( x \sim 0.9 \), with a deviation from unity of less than 2%. Furthermore, the dependence on the nuclear wave function is very weak. The pattern of behavior of the ratio \( R^* \) has been confirmed in independent calculations by Liuti using the formalism of Ref. \[34\], and by Pace et al. \[35\], using a variational approach to calculate the three-body spectral function.

The dependence of \( R^* \) on the input nucleon structure function parameterization is illustrated in Figure 2 (right), where several representative curves at \( Q^2 = 10 \) (GeV/c)^2 are given: apart from the standard CTEQ fit (solid), the results for the GRV \[36\] (dot-dashed), Donnachie-Landshoff (DL) \[37\] (dashed), and BBS \[18\] (dotted) parameterizations are also shown (the latter at \( Q^2 = 4 \) (GeV/c)^2). Despite the seemingly strong dependence on the nucleon structure function input at very large \( x \), this dependence is actually artificial. In practice, once the ratio \( F_2^{3\text{He}}/F_2^{3\text{H}} \) is measured, one can employ an iterative procedure to eliminate this dependence altogether. Namely, after extracting \( F_2^n/F_2^p \) from the data using some calculated \( R^* \), the extracted \( F_2^n \) can then be used to compute a new \( R^* \), which is then used to extract a new and better value of \( F_2^n/F_2^p \). This procedure is iterated until convergence is achieved and a self-consistent solution for the extracted \( F_2^n/F_2^p \) is obtained. Both Afnan et al. \[27\] and Pace et al. \[35\] have independently confirmed the convergence of this procedure.

All of the above suggest that, for the purpose of this investigation, it is reasonable and safe to assume that we can describe \( R^* \) with a central value and assign a systematic uncertainty that grows from 0% at \( x = 0 \) to ±1% at \( x = 0.82 \). Further theoretical investigations in the future could possibly reduce this uncertainty.
Figure 2: Left: Ratio of nuclear EMC ratios for $^3$He and $^3$H for various nuclear model wavefunctions as calculated by Afnan et al. [27] using the CTEQ nucleon structure function parametrization (see text). Right: Ratio of nuclear EMC ratios for $^3$He and $^3$H with the Paris (EST) wave functions, using various nucleon structure function parameterizations [27] (see text).

5 The Experiment

The proposed energy upgrade of Jefferson Lab (JLab) will offer a unique opportunity to perform deep inelastic scattering off the $^3$He and $^3$H mirror nuclei at large-$x$ values. The DIS cross section for $^3$H and $^3$He is given in terms of their $F_1$ and $F_2$ structure functions by Equation 1, where $M$ represents in this case the nuclear mass. The nuclear structure functions $F_1$ and $F_2$ are connected through the ratio $R = \sigma_L/\sigma_T$, where $\sigma_L$ and $\sigma_T$ are the virtual photoabsorption cross sections for longitudinally and transversely polarized photons, by $F_1 = [F_2(1 + Q^2/\nu^2)]/[2x(1 + R)]$. The ratio $R$ has been measured to be independent of the mass number, $A$, in precise SLAC and CERN measurements using hydrogen, deuterium, iron and other nuclei (for a compilation of data see Ref. [28]).

By performing the tritium and helium measurements under identical conditions, using the same incident beam and scattered electron detection system configurations (same $E$, $E'$ and $\theta$), and assuming that the ratio $R$ is the same for both nuclei, the ratio of the DIS cross sections for the two nuclei will provide a direct measurement of the ratio of their $F_2$ structure functions: $\sigma(^3\text{H})/\sigma(^3\text{He}) = F_2(^3\text{H})/F_2(^3\text{He})$.

The key issue for this experiment will be the availability of a high density tritium target. Tritium targets have been used in the past to measure the elastic form factors of $^3$H at Saclay [38] and MIT-Bates [39]. The Saclay target contained liquid $^3$H at 22 K and was able to tolerate beam currents up to 10 $\mu$A with very well understood beam-induced density changes. The tritium density (0.271 g/cm$^3$) at the operating conditions of this target was
known to ±0.5% (based on actual density measurements). The MIT-Bates target contained gas $^3$H at 45 K/15 atm and was able to tolerate beam currents up to 25 $\mu$A with measurable small density changes. The tritium density, under these operating conditions, has been determined to be 0.028 g/cm$^3$ with $\sim$ ±2% uncertainty, using the Virial formalism.

Given a tritium target, an entire program of elastic, quasielastic and inelastic measurements will be possible at JLab. This program can be better accomplished by building a target similar to the MIT-Bates one (the cooling mechanism of a target similar to the Saclay one would prevent coincidence measurements). The tritium density can be better determined from comparison of the elastic cross section measured with the 45 K/15 atm cell and a cell filled up with tritium at higher temperatures (ideal gas of known density). Two more cells will also be necessary for the $^3$He measurements.

The availability of the proposed Medium Acceptance Device (MAD) JLab Hall A spectrometer [40] will facilitate high statistics DIS cross section measurements ($\leq$ ±0.25%) in a large-$x$ range as well as valuable systematics checks. The performance of the above spectrometer is expected to be comparable, if not better, to that of the SLAC 8 GeV/c spectrometer that has provided precise measurements for absolute DIS cross sections, DIS cross section ratios, and differences in $R$ for several nuclei [25, 41, 42]. The overall systematic errors for these measurements have been typically ±2%, ±0.5% and ±0.01, respectively. Since the objective of the experiment is based on measurements of cross section ratios, many of the experimental errors that plague absolute cross section measurements will cancel out. The experimental uncertainties on the ratio of cross sections should be similar to those achieved by SLAC experiments E139 [25] and E140 [41, 42], which were typically around ±0.5%.

DIS scattering with the proposed 11 GeV JLab electron beam can provide measurements for the $^3$H and $^3$He $F_2$ structure functions in the $x$ range from 0.10 to 0.82. The electron scattering angle will range from 12° to 47° and the electron scattered energy from 1 to 4 GeV. Assuming $^3$H and $^3$He luminosities of $\sim 5 \times 10^{37}$ cm$^{-2}$ s$^{-1}$, the time required for the above “core” set of measurements has been estimated to be less than a week. The DIS cross section has been estimated to be between 0.01 and 100 nb/sr/GeV assuming that $\sigma(^3He) \approx 2\sigma_p + \sigma_n$ and $\sigma(^3H) \approx 2\sigma_d - \sigma_p$, and using values for the proton ($\sigma_p$) and deuteron ($\sigma_d$) DIS cross sections and the ratio $R$ from the SLAC “global” analysis [22]. It is evident that such an experiment will be able to provide very high statistics data and perform necessary systematic studies in a very timely fashion.

An important systematic check will be to confirm that the ratio $R$ is the same for $^3$H and $^3$He. The 11 GeV beam and the momentum and angular range of MAD will allow measurements of $R$ in the same $x$ range as in the SLAC experiments by means of a Rosenbluth separation. The $R$ measurements will be limited by inherent systematics uncertainties rather than statistics as in the SLAC case. It is estimated that the $R$ measurements will require an amount of beam time comparable to the one required for the above core set of measurements.

The $F_2(^3H)/F_2(^3He)$ ratio is expected to be dominated by experimental uncertainties that do not cancel in the DIS cross section ratio of $^3$H to $^3$He and the theoretical uncertainty in the calculation of the ratio $R^*$. Assuming that the target densities can be known to the ±0.5% level and that the relative difference in the $^3$H and $^3$He radiative corrections would be
Figure 3: Projected data for the $F_{2n}/F_{2p}$ structure function (left) and $d/u$ quark (right) ratios from the proposed $^3\text{H}/^3\text{He}$ JLab DIS experiment. The error bars include experimental and theoretical systematic uncertainties added in quadrature. The shaded band indicates the present uncertainty due to possible binding effects in deuteron.

±0.5% as in Refs [25, 41], the total experimental error in the DIS cross section ratio of $^3\text{H}$ to $^3\text{He}$ should be $\sim \pm 1.0\%$. Such an error is comparable to a realistic maximum theoretical uncertainty ($\sim \pm 1\%$ in the vicinity of $x = 0.8$) in the calculation of the ratio $R^*$. The quality of the projected data for the $F_{2n}/F_{2p}$ and $d/u$ ratios is shown in Figure 3. The error bars assume a ±1% overall systematic experimental error in the measurement of the $\sigma(^3\text{H})/\sigma(^3\text{He})$ ratio and a theoretical uncertainty in $R^*$ that increases linearly from 0% at $x = 0$ to ±1% at $x = 0.82$. The shaded areas in Fig. 3 indicate the present uncertainty due to possible nuclear corrections in the extraction of $F_{2n}/F_{2p}$ and $d/u$ from deuterium data. It is evident that the proposed measurement will be able to unquestionably distinguish between the present competing extractions of the $F_{2n}/F_{2p}$ and $d/u$ ratios from proton and deuterium DIS measurements, and determine their values with an unprecedented precision in an almost model-independent way.

A secondary goal of this experiment is the precise determination of the EMC effect in $^3\text{H}$ and $^3\text{He}$. At present time, the precision of the available SLAC and CERN data allow for two equally compatible parametrizations [25] of the EMC effect. In the first one, the EMC effect is parametrized versus the mass number $A$ and in the second one versus the nuclear density $\rho$. While the two parametrizations are indistinguishable for heavy nuclei, they predict quite distinct patterns for $A = 3$. This is exhibited in Figure 4, which shows the isoscalar
Figure 4: The $^3$H and $^3$He isoscalar EMC effect ratios $F_2(^3H)/F_2(d)$ and $F_2(^3He)/F_2(d)$ as predicted [25] by the atomic mass $A$ model and the nuclear density $\rho$ model. Also shown are recent data from the Hermes/DESY experiment [43].

EMC ratios of $^3$H and $^3$He. The solid curve in Fig. 4 assumes that the EMC effect scales with $A$ and describes both $A = 3$ nuclei. The dashed and dot-dashed curves assume that the EMC effect scales with $\rho$, applied to $^3$He and $^3$H, respectively. Also shown in Fig. 4 are the recent DESY-Hermes data [43] on the EMC effect for $^3$He. The expected precision (±1%) of this experiment for the $F_2(^3H)/F_2(^3He)$ ratio should easily allow to distinguish between the two competing parametrizations. The new measurements should bring a closure to the EMC effect parametrization issue and provide crucial input for a more complete explanation of the origin of the EMC effect.

6 Summary

We discussed possible DIS measurements with the $A = 3$ mirror nuclei using the 11 GeV upgraded JLab beam. The measurements can determine in an almost model-independent way the fundamental $F_n^2/F_p^2$ structure function and $d/u$ quark distribution ratios at high $x$, and distinguish between predictions based on perturbative QCD and non-perturbative models. The precision of the measurements can improve dramatically the quality of parton distribution parametrizations at high $x$, which are needed for the interpretation of high energy collider data. The expected data can also test competing parametrizations of the nuclear EMC effect and provide valuable constraints on models of its dynamical origin.
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