

ADP-00-28/T411

JLAB-THY-00-17

PCCF RI 00-11

KSUCNR-107-00

Neutron Structure Function and $A = 3$ Mirror Nuclei

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Abstract

We demonstrate that the free neutron structure function can be extracted in deep-inelastic scattering from $A = 3$ mirror nuclei, with nuclear effects canceling to within 2% for $x \lesssim 0.85$.

I. INTRODUCTION

One of the most fundamental properties of the nucleon is the structure of its valence quark distributions. Unlike the sea, which is generated via both perturbative and non-perturbative mechanisms, the valence quark structure reflects entirely large distance dynamics in the nucleon, which cannot be described within perturbative quantum chromodynamics.

Experimentally, most of the recent studies of nucleon structure have emphasized the small- x region populated mainly by sea quarks (x being the fraction of momentum of the nucleon carried by the quark), while the valence quark structure has for some time now been thought to be understood. This is to some extent true, albeit with one major exception — the so-called deep valence region, at very large x , $x \gtrsim 0.7$. Recently it has become more widely appreciated that knowledge of quark distributions at large x is essential for a number of reasons. Not least of these is the necessity of understanding backgrounds in collider experiments, such as in searches for new physics beyond the standard model [1]. Furthermore, the behavior of the d/u quark distribution ratio in the limit $x \rightarrow 1$ is a critical test of the mechanism of spin-flavor symmetry breaking in the nucleon, and of the onset of perturbative behavior in large- x structure functions.

The most widely used source of information about the valence quark distributions in the nucleon has been the proton structure function, F_2^p , which at large x measures a charge-squared weighted combination of the valence u and d distributions. Because the u quark is weighted by a factor 4:1 compared with the d , the F_2^p structure function most directly constrains the u quark distribution.

To determine the individual isospin distributions separately requires a second linear combination of u and d , which traditionally is obtained from the neutron structure function, F_2^n , and which could in principle constrain the d quark distribution as well as the u . However, the absence of free neutron targets means that usually the deuteron is used as an effective neutron, with the neutron structure function approximated by $F_2^n \approx F_2^d - F_2^p$. While this approximation is valid at moderate x , it breaks down dramatically for $x \gtrsim 0.4$ due to Fermi

motion and nuclear binding effects in the deuteron [2–5].

The problem of extracting neutron structure functions from nuclear data is rather old [2], although recently the discussion has been revived with the realization [5] that F_2^n , extracted from F_2^d by taking into account Fermi motion and binding (off-shell) effects, could be significantly larger than that extracted in earlier analyses in which only Fermi motion corrections were applied. In particular, omitting nuclear binding corrections can introduce errors of up to 50% [5,6] in F_2^n/F_2^p already at $x \sim 0.75$. Such a difference is of the same order of magnitude as the variation of the behavior of the F_2^n/F_2^p ratio predicted in the $x \rightarrow 1$ limit, which ranges from 1/4 in non-perturbative models where the d quark is suppressed relative to u [7], to 3/7 in perturbative QCD-inspired models which emphasize helicity aligned configurations of the quark and nucleon [8].

Although one can make a strong argument that a proper treatment of nuclear corrections in the deuteron should account for both Fermi motion as well as binding effects, the question can ultimately be settled only by experiment. In this paper we suggest how this can be achieved by using a novel method which maximally exploits the mirror symmetry of $A = 3$ nuclei. Regardless of the absolute value of the nuclear EMC effects in ${}^3\text{He}$ or ${}^3\text{H}$, the differences between these will be small — on the scale of charge symmetry breaking in the nucleus — which allows a relatively clean determination of F_2^n over a large range of x essentially free of nuclear contamination.

The argument is actually rather simple. In the absence of the Coulomb interaction and in an isospin symmetric world the properties of a proton (neutron) bound in a ${}^3\text{He}$ nucleus would be identical to that of a neutron (proton) bound in ${}^3\text{H}$. If, in addition, the proton and neutron distributions in ${}^3\text{He}$ (and in ${}^3\text{H}$) were identical, the neutron structure function could be extracted with no nuclear corrections, regardless of the size of the EMC effect in ${}^3\text{He}$ or ${}^3\text{H}$ separately.

In practice, ${}^3\text{He}$ and ${}^3\text{H}$ are of course not perfect mirror nuclei — their binding energies for instance differ by some 10% — and the p and n 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. In a self-consistent framework one can use the same NN interaction which describes the two-nucleon system (e.g. NN scattering, deuteron form factors, quasi-elastic ed scattering) to provide the basic input interaction into the three-nucleon calculation. Therefore the wave functions can be tested against a large array of observables which put rather strong constraints on the models.

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

$$R({}^3\text{He}) = \frac{F_2^{3\text{He}}}{2F_2^p + F_2^n}, \quad (1a)$$

$$R({}^3\text{H}) = \frac{F_2^{3\text{H}}}{F_2^p + 2F_2^n}, \quad (1b)$$

one can write the ratio of these as:

$$\mathcal{R} = \frac{R({}^3\text{He})}{R({}^3\text{H})}. \quad (2)$$

Inverting this expression directly yields the ratio of the free neutron to proton structure functions:

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{3\text{He}}/F_2^{3\text{H}}}{2F_2^{3\text{He}}/F_2^{3\text{H}} - \mathcal{R}}. \quad (3)$$

We stress that F_2^n/F_2^p extracted via Eq.(3) does not depend on the size of the EMC effect in ${}^3\text{He}$ or ${}^3\text{H}$, but rather on the *ratio* of the EMC effects in ${}^3\text{He}$ and ${}^3\text{H}$. If the neutron and proton distributions in the $A = 3$ nuclei are not dramatically different, one might expect $\mathcal{R} \approx 1$. 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, $x \gtrsim 0.3$, is the impulse approximation, in which the virtual photon scatters incoherently from individual nucleons in the nucleus [9]. The nuclear cross section is determined by factorizing the γ^* -nucleus interaction into γ^* -nucleon and nucleon-nucleus amplitudes. In the absence of relativistic and nucleon off-shell corrections [10,11], the structure function of a nucleus, F_2^A , can then be calculated by folding the nucleon structure function, F_2^N , with a nucleon momentum distribution in the nucleus, $f_{N/A}$:

$$F_2^A(x) = \int dy f(y) F_2^N(x/y) \equiv f(x) \otimes F_2^N(x) , \quad (4)$$

where y is the fraction of the ‘plus’-component of the nuclear momentum carried by the interacting nucleon, and the Q^2 dependence in the structure functions is implicit. The convolution expression in Eq.(4) 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_1^N structure function, although these are suppressed by powers of M^2/Q^2 , where M is the nucleon mass. Corrections to the impulse approximation appear in the guise of final state interactions, multiple rescattering (nuclear shadowing), NN correlations and 6-quark clusters, however, these are generally confined to either the small- x [12], or very large- x ($x \gtrsim 0.9$) [13] regions.

The distribution $f(y)$ of nucleons in the nucleus is related to the nucleon spectral function $S(p)$ by [9]:

$$f(y) = \int d^3\vec{p} \left(1 + \frac{p_z}{p_0}\right) \delta\left(y - \frac{p_0 + p_z}{M}\right) S(p) , \quad (5)$$

where p is the momentum of the bound nucleon, and is normalized such that $\int dy f(y) = A$. For an $A = 3$ nucleus the spectral function is evaluated from the three-body nuclear wave function, calculated by solving the homogeneous Faddeev equation with a given two-body interaction. Details of the computation of the wave functions can be found in Ref. [14]. To examine the model dependence of the distribution function we use several different potentials, namely the ‘‘EST’’ (Ernst-Shakin-Thaler) separable approximation to the Paris potential [15] (referred to as ‘‘PEST’’), the unitary pole approximation [16] to the Reid Soft Core (RSC) potential, and the Yamaguchi potential [17] with 7% mixing between 3S_1 and 3D_1 waves.

In terms of the proton and neutron momentum distributions, the F_2 structure function for ${}^3\text{He}$ is given by:

$$F_2^{3\text{He}} = 2 f_{p/3\text{He}} \otimes F_2^p + f_{n/3\text{He}} \otimes F_2^n . \quad (6a)$$

Similarly for ${}^3\text{H}$, the structure function is evaluated from the proton and neutron momentum distributions in ${}^3\text{H}$:

$$F_2^{3\text{H}} = f_{p/3\text{H}} \otimes F_2^p + 2 f_{n/3\text{H}} \otimes F_2^n . \quad (6\text{b})$$

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

$$f_{n/3\text{H}} \approx f_{p/3\text{He}} , \quad (7\text{a})$$

$$f_{p/3\text{H}} \approx f_{n/3\text{He}} , \quad (7\text{b})$$

although in practice we consider both the isospin symmetric and isospin symmetry breaking cases explicitly. Note that even in the isospin symmetric case the proton and neutron distributions in ${}^3\text{He}$ will be different because while the neutron in ${}^3\text{He}$ is accompanied by a spectator pp , the spectator system of the proton is either an uncorrelated pn pair or a recoiling deuteron.

The ratio \mathcal{R} of EMC ratios for ${}^3\text{He}$ and ${}^3\text{H}$ is shown in Fig. 1 for the various nuclear model wave functions (PEST, RSC and Yamaguchi), using the CTEQ parameterization [18] of parton distributions at $Q^2 = 10 \text{ GeV}^2$ for F_2^N . The EMC effects are seen to largely cancel over a large range of x , out to $x \sim 0.85 - 0.9$, with the deviation from a ‘central value’ $\mathcal{R} \approx 1.01$ within $\pm 1\%$. Furthermore, the dependence on the nuclear wave function is very weak. In practice, the exact shape of \mathcal{R} will not be important for the purposes of extracting F_2^n/F_2^p from the $F_2^{3\text{He}}/F_2^{3\text{H}}$ ratio; rather, it is essential that, as we find, the model dependent deviation of \mathcal{R} from the central value should be small.

The dependence of \mathcal{R} on the input nucleon structure function parameterization is illustrated in Fig. 2, where several representative curves at $Q^2 = 10 \text{ GeV}^2$ are given: apart from the standard CTEQ fit (solid), the results for the GRV [19] (dot-dashed), Donnachie-Landshoff (DL) [20] (dashed), and BBS [21] (dotted) parameterizations are also shown (the latter at $Q^2 = 4 \text{ GeV}^2$). For $x \lesssim 0.6$ there is little dependence ($\lesssim 0.5\%$) in the ratio on the structure function input. For $0.6 \lesssim x \lesssim 0.85$ the dependence is greater, but still with $\lesssim \pm 1\%$ deviation away from the central value $\mathcal{R} \approx 1.01$. The spread in this region is due mainly to the poor knowledge of the neutron structure function at large x . Beyond $x \approx 0.85$

there are few data in the deep-inelastic region on either the neutron or proton structure functions, so here both the d and u quark distributions are poorly determined.

A standard assumption in most global fits of parton distributions is that $d/u \rightarrow 0$ as $x \rightarrow 1$. This assumption has recently been questioned on theoretical and phenomenological grounds [5,22,23]. The BBS parameterization [21], on the other hand, incorporates constraints from perturbative QCD, and forces $d/u \rightarrow 0.2$ as $x \rightarrow 1$ [8]. The effect of the different large- x behavior of the d quark is apparent only for $x \gtrsim 0.85$, where it gives a difference of ~ 1 – 2% in \mathcal{R} compared with the fits in which $d/u \rightarrow 0$. One can also modify the standard CTEQ fit, for example, by applying a correction factor [22] to enforce $d/u \rightarrow 0.2$, however, this also produces differences in \mathcal{R} which are $\lesssim 2\%$ for $x < 0.9$.

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 \mathcal{R} , the extracted F_2^n can then be used to compute a new \mathcal{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 and \mathcal{R} is obtained.

All of the structure functions discussed thus far have been calculated assuming leading twist dominance at $Q^2 = 10 \text{ GeV}^2$. To test the sensitivity of the ratio to possible effects beyond leading twist, we have calculated \mathcal{R} using the fit to the total F_2 structure function from Donnachie and Landshoff [20], which has an explicit higher twist ($\propto 1/Q^2$) component in addition to the leading twist. The result is indicated by the upper dot-dashed curve DL(HT) in Fig. 2. The difference between the leading twist only and leading + higher twist curves is negligible for $x \lesssim 0.8$, increasing to $\sim 1.5\%$ at $x \sim 0.85$, where higher twist effects are known to be more important. The size of the higher twist corrections can be determined by taking measurements at several values of Q^2 and observing any $1/Q^2$ dependence of the structure function. In particular, since the Q^2 dependence of F_2^p has been measured in a number of earlier experiments [24], the Q^2 dependence of the extracted F_2^n/F_2^p can be used

to separate the leading twist from the non-leading twist components of F_2^n .

We conclude therefore that the effect on \mathcal{R} from the present lack of knowledge of the nucleon structure function is $\lesssim 2\%$ for $x \lesssim 0.85$. However, this uncertainty can in principle be eliminated altogether via an iteration procedure, so that the only model dependence of \mathcal{R} will be from the nuclear interaction in the $A = 3$ nucleus.

The ratios in Fig. 1 were calculated using three-nucleon wave functions neglecting the Coulomb interaction and working in an isospin basis (we also omit possible three-body forces since these are expected to have a negligible effect on \mathcal{R}). To estimate the effect of neglecting the Coulomb interaction in ${}^3\text{He}$ and at the same time correct the long range part of the three-body wave function due to the change in the binding energy, we have modified the 1S_0 potential in ${}^3\text{He}$ and ${}^3\text{H}$ to reproduce their respective experimental energies. In this way the ${}^3S_1 - {}^3D_1$ interaction responsible for the formation of the deuteron is unchanged. This approximation spreads the effect of the Coulomb interaction over both the pp and np interaction in the 1S_0 channel. To that extent, it shifts some of the Coulomb effects in the neutron distribution in ${}^3\text{He}$ to the proton distribution. However, this simple modification to the 1S_0 interaction will allow us to study explicitly the possible effects associated with the differences in the binding energies of ${}^3\text{He}$ and ${}^3\text{H}$.

The ratio \mathcal{R} calculated with the PEST wave function modified according to this prescription is shown in Fig. 3, labeled PEST(E) (dashed curve). (The CTEQ parameterization of the nucleon structure function at $Q^2 = 10 \text{ GeV}^2$ is used.) The result of this modification is a shift of approximately 0.5–1% shift in \mathcal{R} , with the net effect still being a ratio which deviates by $< 2\%$ from unity.

Also shown in Fig. 3 is the prediction of the nuclear density model, extrapolated from heavy nuclei to $A = 3$ [25]. The nuclear density model, which has proven successful for studying the A -dependence of the EMC effect for heavy nuclei, stems from the empirical observation that for heavy nuclei the deviation from unity in the EMC ratio is assumed to scale with nuclear density:

$$\frac{R(A_1) - 1}{R(A_2) - 1} = \frac{\rho(A_1)}{\rho(A_2)}, \quad (8)$$

where $\rho(A)$ is the mean nuclear density. From the empirical $A = 3$ charge radii one finds that $\rho(^3\text{H})/\rho(^3\text{He}) \approx 140\%$, so that the EMC effect in ^3H is predicted to be $\sim 40\%$ bigger than in ^3He . However, assuming that $R(^3\text{He})$ can be extrapolated from the measured EMC ratios for heavy nuclei such as ^{56}Fe , one still finds that ratio $|\mathcal{R} - 1| < 2\%$ for all $x \lesssim 0.85$. Although there are questions about the meaning of nuclear density for a few-body system [26], it is reassuring to see that practically the entire range of models of the nuclear EMC effect predict that \mathcal{R} is within 1–2% of unity for all $x \lesssim 0.85$.

The ideal place to carry out a high- x deep-inelastic scattering (DIS) experiment on ^3He and ^3H [27,28] is Jefferson Lab (JLab) with its proposed energy upgrade to 12 GeV. Since the ratio of longitudinal to transverse photoabsorption cross sections $R = \sigma_L/\sigma_T$ is the same for ^3He and ^3H , measurements of the ^3He and ^3H DIS cross sections under identical conditions can provide a direct measurement of the ratio of the F_2 structure functions of the two nuclei: $\sigma(^3\text{H})/\sigma(^3\text{He}) = F_2^{^3\text{H}}/F_2^{^3\text{He}}$. The key issue for the experiment will be the availability of a high density ^3H tritium target similar to those used in the past to measure the elastic form factors of ^3H at Saclay [29] and MIT-Bates [30]. The high intensity of the JLab beam and the large acceptance of existing or proposed JLab spectrometers will facilitate high statistics DIS cross section measurements ($\leq \pm 0.25\%$) over a large x range ($0.10 \leq x \leq 0.83$) and valuable systematics checks in a data taking period of just a few weeks.

The measured $F_2^{^3\text{H}}/F_2^{^3\text{He}}$ ratio is expected to be dominated by experimental uncertainties that do not cancel in the DIS cross section ratio of ^3H to ^3He , and the theoretical uncertainty in the calculation of \mathcal{R} . Assuming that the target densities can be known to the $\simeq 0.5\%$ level and that the relative difference in the ^3H and ^3He radiative corrections would be $\simeq 0.5\%$, the total experimental error in the DIS cross section ratio of ^3H to ^3He should be $\leq 1.0\%$ (similar to the error of past DIS measurements of the proton to deuteron cross section ratio [31]). Such an error is comparable to the present theoretical uncertainty in the calculation of the ratio \mathcal{R} .

Figure 4 shows the presently available data on F_2^n/F_2^p , adjusted for the JLab 12 GeV kinematics, as extracted from the SLAC deep-inelastic $\sigma(p)$ and $\sigma(d)$ cross sections using a Fermi-smearing model with the Paris nucleon–nucleon potential [6]. To indicate the quality of the proposed F_2^n/F_2^p ratio determination from the $\sigma(^3\text{H})/\sigma(^3\text{He})$ measurement, we plot in Fig. 4 the \pm one standard deviation projected error band for the x range accessible with a 12 GeV upgraded JLab beam. The band includes both projected experimental and theoretical uncertainties. The central values of the band represent F_2^n/F_2^p determined using the density model [25] for the nuclear EMC effect and data on EMC ratios for heavy nuclei from the SLAC experiment E139 [32]. It is evident, therefore, that the proposed measurement will be able to unambiguously distinguish between the two different methods of extracting the F_2^n/F_2^p ratio from proton and deuterium DIS measurements, and determine its value for large x with an excellent precision in an (almost) independent model way.

As well as offering a relatively clean way to extract F_2^n/F_2^p , DIS from the $^3\text{He}/^3\text{H}$ system can also determine the absolute size of the EMC effect in $A \leq 3$ nuclei. With F_2^n determined from the combined $F_2^{^3\text{He}}/F_2^{^3\text{H}}$ and F_2^p structure functions, the size of the EMC effect in the deuteron (namely, $F_2^d/(F_2^p + F_2^n)$) can be deduced from the measured F_2^d/F_2^p ratio. This would settle a question which has remained controversial since the early 1970s. Furthermore, data on the absolute values of $F_2^{^3\text{He}}$ and $F_2^{^3\text{H}}$ will also allow the absolute value of the EMC effect in $A = 3$ nuclei to be determined. To date the only data on $F_2^{^3\text{He}}$ in existence are those from the HERMES experiment [33], which measured the ratio $\sigma(^3\text{He})/(\sigma(d) + \sigma(p))$, although the focus there was the region of small x and Q^2 .

In summary, we have demonstrated the effectiveness of using $A = 3$ mirror nuclei to extract the ratio of the neutron to proton structure functions, F_2^n/F_2^p , free of nuclear effects to $< 2\%$ for all $x \lesssim 0.85$. A successful program of DIS measurements of $A = 3$ cross sections at an energy-upgraded Jefferson Lab would not only settle a “text-book” issue which has eluded a definitive resolution for nearly 30 years, but would also allow the completion of the empirical study of nuclear effects in deep-inelastic scattering over the full range of mass numbers.

ACKNOWLEDGMENTS

We would like to thank S. Liuti, G. Salme, S. Scopetta and S. Simula for helpful discussions and communications. This work was supported by the Australian Research Council, the US Department of Energy contract DE-AC05-84ER40150, and the US National Science Foundation grant PHY-9722640.

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FIGURES

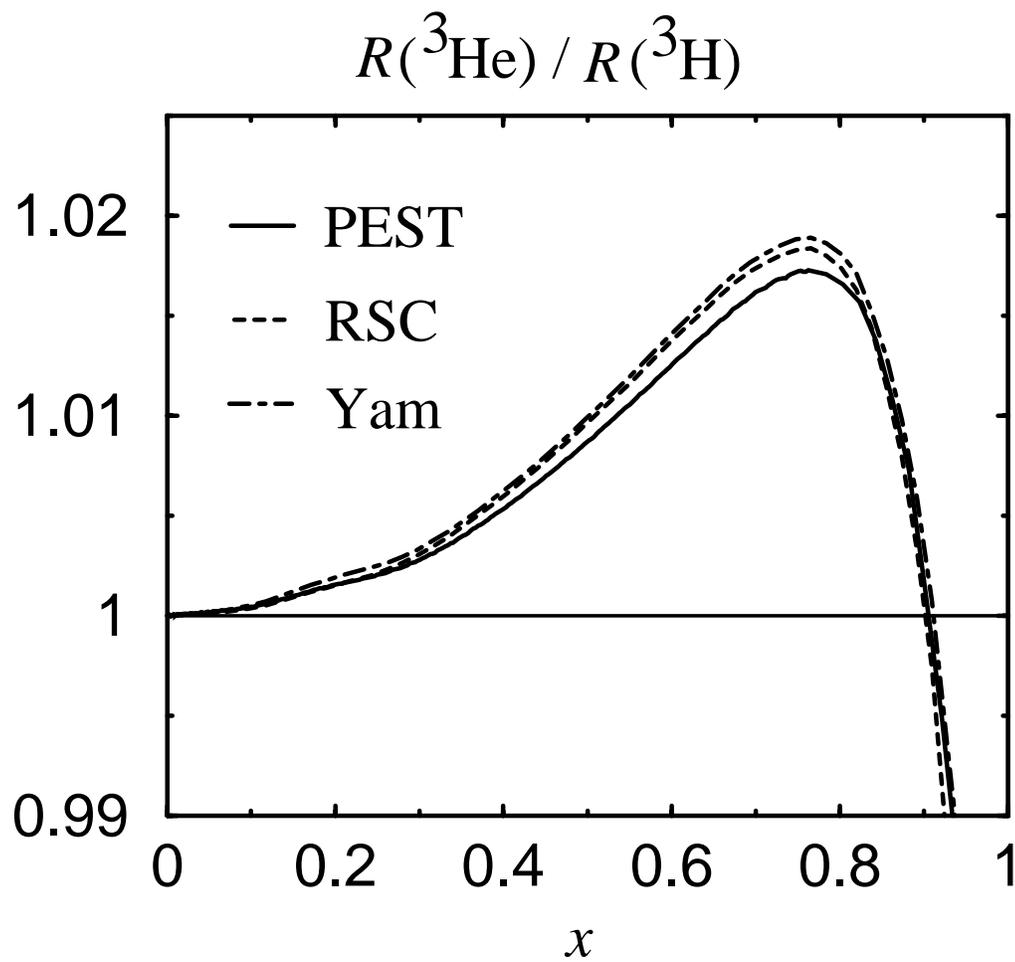


FIG. 1. Ratio of nuclear EMC ratios for ^3He and ^3H for various nuclear models: PEST (solid), Reid Soft Core (dashed), Yamaguchi (dot-dashed).

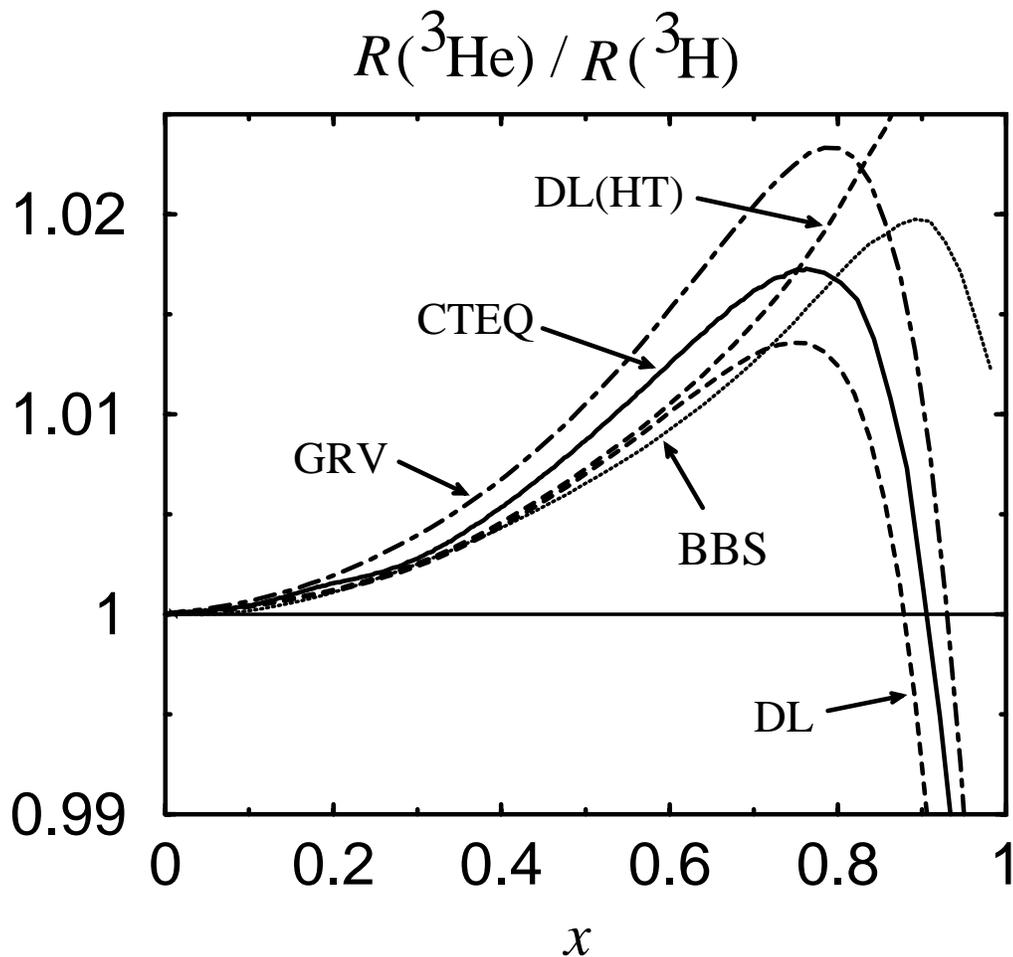


FIG. 2. Ratio of nuclear EMC ratios for ${}^3\text{He}$ and ${}^3\text{H}$ with the PEST wave functions, using various nucleon structure function parameterizations: CTEQ (solid), GRV (dot-dashed), BBS (dotted), and Donnachie-Landshoff (DL) with leading twist only, and with higher twist (HT) correction (dash-dotted).

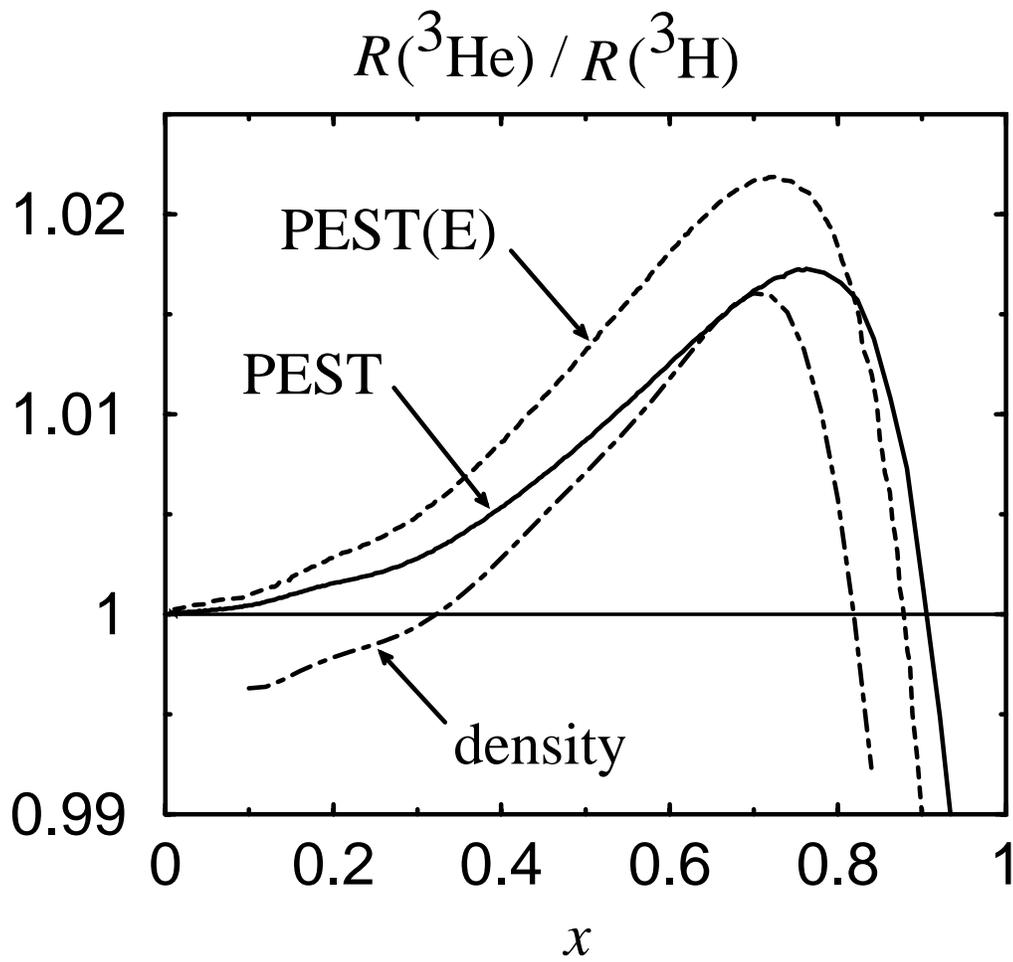


FIG. 3. Ratio of nuclear EMC ratios for ${}^3\text{He}$ and ${}^3\text{H}$ for the PEST wave function (solid), modified PEST to reproduce the experimental binding energies (dashed), and the density extrapolation model (dot-dashed).

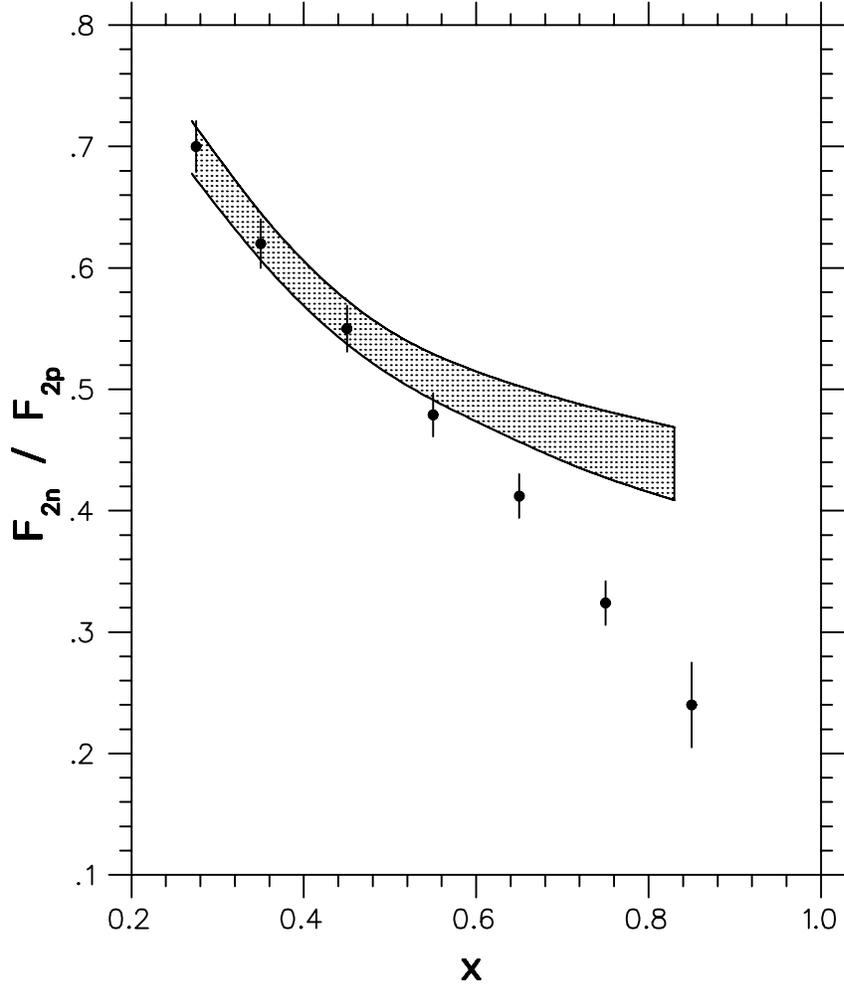


FIG. 4. F_2^n/F_2^p ratio extracted from previous deep-inelastic p and d cross sections using a Fermi-smearing model [6] (solid circles). The shaded band represents a \pm one standard deviation error for the proposed ^3H and ^3He DIS JLab experiment, with the central values of the band corresponding to F_2^n/F_2^p extracted assuming an EMC effect in deuterium (see text).