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Extracting the neutron structure function*

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ABSTRACT. Nuclear effects in deep scattering experiments play an important role in the extraction of the neutron structure function. Traditionally, these effects have been neglected when the extraction from combined experimental data on proton and deuteron is performed. As the neutron structure function participates in the verification of quark-parton sum rules and QCD predictions, these effects have appreciable consequences and, in fact, have led to several failures in these kind of verifications. At the same time, model estimates of these effects bring accordance between data and theoretical expectations. The present article aims to review and summarize results on these topics.

RESUMEN. Los efectos nucleares en la dispersión inelástica profunda juegan un papel importante en la extracción de la función de estructura del neutrón. Tradicionalmente, estos efectos han sido despreciados cuando la extracción se hace a partir de datos experimentales combinados sobre protones y deuterones. Dado que la función de estructura del neutrón participa en la verificación de reglas de suma del modelo de quark-partones y predicciones de QCD, estos efectos tienen consecuencias apreciables y, de hecho, llevan a resultados no esperados en este tipo de verificaciones. Al mismo tiempo, estimaciones de estos efectos a partir de modelos sobre el deuterón explican el desacuerdo entre predicciones teóricas y experimento. Este artículo intenta revisar y resumir los resultados sobre este tópico

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1. INTRODUCTION

Deep inelastic scattering is one of the most valuable tools for unveiling the structure of hadrons. In the past, it has been fundamental for establishing the quark parton model and for testing QCD predictions related to the scaling violations in the nucleon structure functions. Current deep inelastic scattering experiments have attained sufficient accuracy as to establish the running character of the strong coupling constant predicted by QCD and to determine parton distributions from the measured structure functions.

These experiments also provide information about nucleon parton distributions in nuclei. The discovery of the nuclear dependence in nuclear structure functions, the so called EMC effect, have stimulated a great deal of interest in this kind of experiments with nuclear targets. The dependence can be understood in terms of modifications of the nucleon structure in the nuclear medium, the consequences of non nucleonic degrees of freedom, etc. As we shall see, this phenomenon plays also an important role in the extraction of the

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neutron structure function, which is commonly performed from combined experimental data on proton and deuteron, even if its effects have been traditionally neglected.

The neutron structure function participates in the verification of several sum rules, which are one of the main goals of the quark parton model and even of more theoretical grounds (precise verifications of QCD predictions). Consecutive failures in this kind of verifications have stimulated several theoretical works in the recent past. Between the different alternative explanations for these failures, the one which claims that the problem is related with the neglected nuclear effects in the deuteron when extracting the neutron structure functions is the most natural, economic and consistent.

Although nuclear effects in the deuteron are small, as one would have expected due to the loosely bound character of this nucleus, sum rules weight them differently leading in some cases to dramatic amplifications. The same can be said regarding QCD tests. Model estimates of these effects based on the pionic content of the deuteron are consistent with the magnitude, shape and scale dependence needed to bring accordance between data and theoretical expectations in different experiments, supporting in this way the viewpoint.

The present article aims to review and summarize results on this topic. Some of them have been published elsewhere in a more comprehensive way.

In the Sect. 2 we analyzed recent NMC data on the ratio of the deep inelastic structure functions F_2 per nucleon for deuterium relative to hydrogen in the context of the Gottfried sum rule (GSR), showing that the discrepancy between Gottfried sum rule prediction and NMC data analysis may be interpreted as a nuclear effect in the deuteron, as it is suggested by several models.

The Sect. 3 is devoted to compare the incidence of these effects in the Drell-Yan proton-neutron asymmetry. The next one analyzes the case of the Bjorken sum rule (BSR). There we show that the small amount of nuclear effects necessary to saturate the GSR experimental data modifies the Drell-Yan asymmetry in an enterily different way as an asymmetric sea does, and that the effects are of little consequence in the convergence of the BSR to the expected value.

In the Sect. 5 we analyse the experimental Q^2-dependence of the ratio F_2^p/F_2^n, also provided by the recent NMC experiment, showing that the unexpected dependence found in the range $x = 0.1 - 0.4$ is also due to the same effects.

The following section shows how a very simple model based on the pionic content of the deuteron reproduces the main features of the nuclear effect providing the magnitude, x- and Q^2-dependence of the nuclear effect, in a very good approximation, with only one free parameter: the fraction of the deuteron momentum carried by its pionic constituents.

Finally we state our general conclusions.

2. THE GOTTFRIED SUM RULE

In the quark-parton model [1] the difference between the proton and the neutron deep inelastic structure functions is expressed in terms of the quark momentum distributions,

namely

$$F_2^p - F_2^n = \frac{x}{3}(u_v - d_v) + \frac{2x}{3}(\bar{u} - \bar{d}). \tag{1}$$

In QCD this expression is valid in leading order or up to the next to leading order in the DIS scheme [2]. This last relation together with the assumption of flavour symmetric sea ends, using the valence distributions normalization, with the well known Gottfried sum rule [3]

$$\int_0^1 \frac{dz}{x}\left(F_2^p - F_2^n\right) = \frac{1}{3}. \tag{2}$$

This sum rule has been tested by different experimental groups; first at SLAC [4], then by the EMC [5] and the BCDMS [6] groups, and more recently, by the NMC at CERN [7]. In the earlier cases the result was found to be lower than but compatible with the expected $\frac{1}{3}$, within the large systematic errors due to the extrapolation of $F_2^p - F_2^n$ into the unmeasured region, $x < 0.02$ (EMC) and $x < 0.06$ (BCDMS). The more recent NMC experiment provides values for the ratio of the structure functions F_2^n/F_2^p obtained in deep inelastic scattering of muons on hydrogen and deuterium targets, exposed simultaneously to the beam. The data cover the kinematic range down to $x = 0.004$ and $Q^2 = 0.4$ GeV^2.

Assuming that nuclear effects are not significant in deuterium, *i.e.*,

$$F_2^D = \tfrac{1}{2}(F_2^p + F_2^n) \tag{3}$$

NMC gives values for $F_2^p - F_2^n$, expressed as

$$F_2^p - F_2^n = 2F_2^D \frac{1 - \dfrac{F_2^n}{F_2^p}}{1 + \dfrac{F_2^n}{F_2^p}}, \tag{4}$$

where

$$\frac{F_2^n}{F_2^p} \equiv 2\frac{F_2^D}{F_2^p} - 1. \tag{5}$$

The absolute deuteron structure function was taken from a fit to previous data obtained in other experiments [8]. The value for the Gottfried sum rule derived in this way from NMC data on F_2^D/F_2^p and a fit for F_2^D is significantly below the quark-parton model prediction [7]:

$$\int_0^1 \frac{dx}{x}(F_2^p - F_2^n) = 0.240 \pm 0.016. \tag{6}$$

Several explanations for this discrepancy have been suggested [8]. One of the main assumptions in the derivation of Eq. (2) is the isospin symmetry of the sea $\bar{u} = \bar{d}$. Releasing this condition, the deviation from $\frac{1}{3}$ can be attributed to

$$\int_0^1 dx\,(\bar{u} - \bar{d}) \sim -0.14. \tag{7}$$

Indeed, Field and Feynman [9] have argued that the Pauli principle ought to make $\bar{u} \neq \bar{d}$, however second order QCD calculations of the evolution of $\bar{u} - \bar{d}$ state that this difference cannot explain the observed difference unless a primordial non perturbative asymmetric sea is assumed [10]. Best fits for the quark distributions seem to prefer the equality.

An alternative explanation [12] is related to the main assumption in the analysis of the data, *i.e.*, that nuclear effects are not significant in deep inelastic scattering off deuterium Eq. (3). Several nuclear models provide predictions for this kind of effects [11], however in this section we shall restrict ourselves to extract and parameterize it from measured data and consistency arguments.

In order to take into account nuclear effects in deuterium, one can define bound nuclear structure functions, F_2', by means of

$$F_2^D = \frac{1}{2}(F_2'^p - F_2'^n), \tag{8}$$

$$F_2'^p = \frac{1}{\beta} F_2^p. \tag{9}$$

Due to isospin symmetry one expects the β factor to be the same for proton and neutron structure functions. Then the difference between bound nucleon structure functions is expressed as

$$F_2'^p - F_2'^n = 2F_2^D \frac{1 - \dfrac{F_2'^n}{F_2'^p}}{1 + \dfrac{F_2'^n}{F_2'^p}} = \frac{1}{\beta}\left[\frac{x}{3}(u_v - d_v) + \frac{2x}{3}(\bar{u} - \bar{d})\right]. \tag{10}$$

The ratio $F_2'^n/F_2'^p$ is related to the one reported by NMC, $F_2^n/F_2^p|_{\mathrm{NMC}}$, through

$$\left.\frac{F_2^n}{F_2^p}\right|_{\mathrm{NMC}} \equiv 2\frac{F_2^D}{F_2^p} - 1 = \frac{1}{\beta}\frac{F_2'^n}{F_2'^p} + \frac{1}{\beta} - 1, \tag{11}$$

$$F_2'^p - F_2'^n = 2F_2^D \left[\frac{2}{\beta\left(\left.\dfrac{F_2^n}{F_2^p}\right|_{\mathrm{NMC}} + 1\right)} - 1\right]. \tag{12}$$

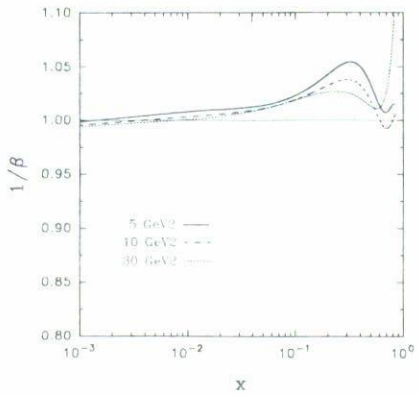

FIGURE 1. The ratio between deuterium and free nucleon structure functions, $1/\beta_D$, for different Q^2 values.

The β parameter can be estimated by using the NMC data combined with a quark distribution parametrization. Notice that the distributions in Eq. (10) should be those of and unbound proton. Unfortunately, data coming from deuteron targets are always used in the fits, however, the inclusions of the β parameter at this level does not modify our conclusions.

The values obtained in this way for $1/\beta$ are presented in Fig. 1. We have used on this occasion the very recent Gluck, Reya and Vogt (LO) parton distributions [13], which are symmetric in the sea ($\bar{u} = \bar{d}$), as is the case in almost any parametrization. These parton distributions are consistent with neutrino and muon deep inelastic data as well as Drell-Yan pair production and are specially suited for low momentum values. In order to obtain values for F_2^D we also have used the parametrization given in reference [14] for F_2^n/F_2^p and Abramowicz *et al.* parametrization [15] for the proton structure function.

It should be noticed that entirely similar results are obtained using other quark distributions, for example Morfin and Tung s-fit in DIS scheme [16] or B_- and B_0 fits of Kwiecinsky, Martin, Stirling and Roberts [17], which also incorporates theoretical QCD results leading to the singular behaviour of the gluon and sea quark distributions as well as modifications due to shadowing effects.

We have also analysed the effect of using a common fit to the SLAC, BCDMS and EMC-NA28 data [18] for structure functions instead of NMC data. This phenomenological parametrizations is based on a detailed comparison of high statistics measurements and fits data in a wide Q^2 range. The resulting $\frac{1}{\beta}$ values are compatible with NMC ones in the x range where this parametrization is supposed to be valid.

Notice that the curves in Fig. 1 exhibit the familiar features of nuclear effects, in particular the antishadowing peak for $x \sim 0.2$ and a pronounced decrease when x tends to one. What seems unusual there is the persistency of antishadowing for small x, however it must be remembered that these curves relate deuterium to hydrogen protons (and not nuclear to deuterium ones), and that shadowing for small x values should be strongly dependent on A. In this way, the effect seems to be a natural extrapolation of what is seen in heavier nuclei. In the last section we will discuss the possible origin of this phenomenon.

A remarkable feature of the Gottfried Sum Rule is that it is an extraordinary amplifier of nuclear effects. In fact, an amount of antishadowing as small as 3% causes a deviation in the integrand as big as 37%. This explains why the beta function is almost independent of the parton distribution used and why up to now this deuteron nuclear effect has been safely neglected in many analysis. As we have mentioned, deuteron data is actually used in the extraction of parton distributions, but no significant change is there detected when β is included. In the next section we will show how these effects are weighted in different sum rules.

3. THE DRELL-YAN ASYMMETRY

In the preceding section, we have shown that the announced experimental violation of the Gottfried sum rule can be understood in terms of nuclear effects in the deuteron structure function from which the neutron one is extracted.

Clearly, the deuteron plays an important role in parton sum rules because there are no direct measurement of the neutron structure function [20]. Our purpose here is to confirm that proposal against the simplest picture of deuteron as the sum of proton plus neutron in a hard scattering experiment. In so doing we have quantitatively analysed the corresponding effects in Drell-Yan asymmetry.

As we mentioned, several alternative interpretations of the discrepancy in the GSR has been recently proposed [8]. The most popular one is based on isospin symmetry violations in the light quark sea of the proton. On this basis, Ellis and Stirling [21] have recently remarked the importance of a Drell-Yan type of experiment because it is very sensitive to this eventual sea modification. As the experiment is also affected by modifications in the valence quark distributions due to nuclear effects, we have evaluated how our treatment of the deuteron structure function also modifies their result.

The main observation in Ref. [21] is related to the asymmetry

$$A_{DY} = \frac{\sigma^{pp} - \sigma^{pn}}{\sigma^{pp} + \sigma^{pn}}, \tag{13}$$

where

$$\sigma^{pN} = s \left. \frac{d^2\sigma^{pN}}{d\sqrt{\tau}\, dy} \right|_{y=0} = \frac{8\pi\alpha^2}{9\sqrt{\tau}} \sum_i e_i^2 (q_i^p(x, M)\bar{q}_i^N(x, M) + p \leftrightarrow N) \tag{14}$$

corresponds to the Drell-Yan process $pN \to l^+l^-X$, in the usual notation. If one neglects the strange and charm quark contributions and retains only the $q_v\bar{q}_s$ contributions in the leading order, the asymmetry takes the form

$$A_{DY} = \frac{(4u_v - d_v)(\bar{u} - \bar{d}) + (u_v - d_v)(4\bar{u} - \bar{d})}{(4u_v + d_v)(\bar{u} + \bar{d}) + (u_v + d_v)(4\bar{u} + \bar{d})}. \tag{15}$$

This asymmetry is very sensitive to the sea distributions, in fact it changes sign depending on whether the sea is flavour symmetric or not. An estimation for this asymmetry using the

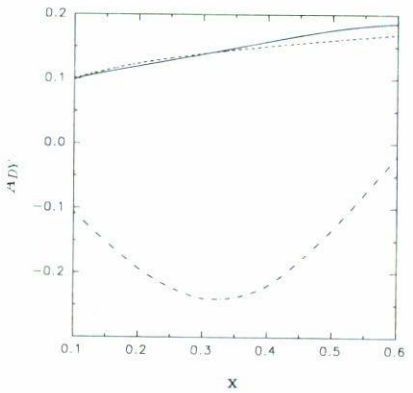

FIGURE 2. The Drell-Yan proton neutron asymmetry with and without nuclear effect (continuous line and dashes respectively), and Ellis and Stirling isospin-broken prediction (dashed-dotted line).

non symmetric sea quark distributions, needed to verify the GSR [21] when nuclear effects are absent, lies between -0.1 and -0.2 for intermediate x values. On the other hand, the standard prediction using parametrizations that are sea symmetric provides $A_{DY} \sim 0.1$ in the same x range. Notice that the actual measurement of the asymmetry can only be done with protons beams on hydrogen or nuclear targets. As quark distributions in deuteron are modified, one can expect a deviation from the standard prediction also in this framework. Again, the simplest way to evaluate this deviation is to consider that nuclear quark distributions are that for free nucleons multiplied by a $\frac{1}{\beta}$ factor. The measured asymmetry then reads

$$A_{DY}\frac{(u_v+\bar{u})(8\bar{u}-\frac{5}{\beta}\bar{d})+(d_v+\bar{d})(2\bar{d}-\frac{5}{\beta}\bar{u})}{(u_v+\bar{u})(8\bar{u}+\frac{5}{\beta}\bar{d})+(d_v+\bar{d})(2\bar{d}+\frac{5}{\beta}\bar{u})}. \tag{16}$$

Figure 2 shows our prediction for the asymmetry using MT parametrizations and beta values obtained as we mentioned earlier (continuous line) and for $\beta = 1$ (dashes). This calculation corresponds to an 800 GeV proton beam on a fixed target, so the lepton pair masses lie between 4 and 20 GeV. The prediction should be compared with the negative values coming from the asymmetric-sea hypotesis in Ref. [21]. Due to the clear cut differences of results coming from the two proposals, one is tempted to urge once more for a experiment on the proton-neutron cross-section asymmetry to definitively decide on the isospin symmetry of the sea.

It must be noticed, that at variance with the proposal in Ref. [21], nuclear effects implemented in this way do not modify the Drell-Yan rapidity distribution due to a cancellation of the β factor. On this basis, the available measurements on, for example, p–Cu collisions seem to favour our suggestion (Fig. 6 of Ref. [21]).

4. THE BJORKEN SUM RULE

We have analyzed a third experimental effect of our proposal referred to the neutron

structure function, now in connection with the Bjorken sum rule [22],

$$\int_0^1 dx\,(g_1^p(x) - g_1^n(x)) = \frac{1}{6}\frac{g_A}{g_V}. \tag{17}$$

The polarized structure functions $g_1^N(x)(N = p, n)$ are related to the unpolarized ones by

$$xg_1^N(x) = A_1^N(x)\frac{F_2^N(x)}{2(1 + R(x))}, \tag{18}$$

where $A_1^N(x)$ stands for the asymmetry in polarized lepton-nucleon scattering and $R(x)$ is the ratio of longitudinal to transverse contributions in the unpolarized case. (R is very small in the kinematic region of interest so it is neglected in our calculations).

The proton asymmetry A_1^p was first measured in 1976 [23], and with better accuracy in 1988 by the EMC [24]. However measurements of the neutron one are not available yet. As this last experiment will require the use of nuclear targets, deuteron in particular, the results will suffer of nuclear effects as in the two preceding cases. There are at least two ways in which this nuclear effects can play a role. The more direct one is related to the asymmetry measurement. In fact, in the quark parton model, this quantity is given by [1]

$$A_1^N(x) = \frac{\sum_i e_i^2(q_i \uparrow (x) - q_i \downarrow (x))}{\sum_i e_i^2(q_i \uparrow (x) + q_i \downarrow (x))}. \tag{19}$$

If we consider nuclear effects in the way we have done up to now, *i.e.*, through a common multiplicative factor in the quark distributions, the effect on the asymmetry obviously cancels. This is of course an approximation because the effective β parameter measures the global effect in the unpolarized structure function and each quark distribution may change in a different way. We should obviously wait until measurements on nuclear targets are available to confirm this point. The second way is related to the use of F_2^n in Eq. (18). The naive extraction of this structure function from the nuclear ones can play an important role as in the GSR. For example, instead of testing the BSR, using nuclear targets we shall be looking at

$$\int_0^1 dx\,(g_1^p(x) - \alpha g_1^n(x)), \tag{20}$$

where $\alpha = F_2^{*n}/F_2^n$, with F_2^{*n} the incorrectly extracted value of this nuclear structure function. In our calculations the typical values are $\alpha \sim 1.05$. Consequently, the convergence of the BSR depends on the relation between g_1^p and g_1^n. If the asymmetries were similar quantities, the violation would be as big as in the GSR. As it was said, there are no measurements available yet, but we can make an estimation using model predictions for A_1^n. We have used Woloshyn estimation for the neutron asymmetry [25], which incorporates sea contributions to the spin dilution model, fits EMC data, and satisfies the BSR. We have found that the incorrect extraction of F_2^n from deuterium targets does not

modify the convergence of the BSR in a significant way. This comes from the fact that in this model the neutron asymmetry is negative in almost all the x region of interest so that the previously mentioned GSR amplification is not present.

5. THE Q^2 DEPENDENCE OF F_2^n/F_2^p

More recently, the NMC Group has reported results on the Q^2–dependence of ratio of neutron and proton structure functions, F_2^n/F_2^p, deduced from the same deep inelastic scattering experiment [14]. In their analysis, they show that the resulting Q^2–dependence of the ratio, in the intermediate x-range (0.1 – 0.4), is stronger than the one predicted by perturbative QCD, and it is suggested that this difference should be attributed to different higher twist contributions for the proton and the neutron. At variance with these results, in earlier QCD analysis of high statistics F_2 data for proton and deuteron separately [26], an excellent agreement with QCD was observed and higher twist terms were found to be similar in hydrogen and deuterium data, and small for $x < 0.4$.

In this section we will show that the unexpected Q^2–dependence of the ratio found by the NMC is explained in terms of the same effects we refereed to in the preceding sections, which distort the naive relation between the proton, the neutron and the deuteron structure functions. In this way the quite exotic higher twist isospin violating effects proposed [14] can be avoided.

The unexpected Q^2–dependence in the NMC analysis of the data confirms our conclusions. Disregarding nuclear effects, again, the relation between the proton and the neutron structure function looks odd, particularly in the intermediate x range, where we had found that they were stronger. There, when corrections are taken properly into account, the discrepancy with QCD fades away.

In the following, we parametrize the effect as in the first section but taking special care in the extraction of its Q^2–dependence, specially for low Q^2 values. Then we modify the NMC ratios with our parametrizations and discuss these results in connection with higher twist terms.

As we are now particularly interested in the consequences of the effects in connection with the Q^2–dependence of the ratio $F_2^n/F_1^p|_{\mathrm{NMC}}$, which runs up to very low values of Q^2, we calculate the β parameter using Gluck, Reya and Vogt parton distributions [13], which are specially suited for such low momentum, and we include target mass corrections in the right hand side of Eq. (10). In order to obtain values for F_2^D we use the parametrization given in reference [14] for $F_2^n/F_2^p|_{\mathrm{NMC}}$, and Abramowicz *et al.* parametrization [15] for the proton structure function.

In Fig. 3 we show the $\frac{1}{\beta}$ function for different Q^2–values, with target mass correction. This curves should be compared with the ones in Fig. 1.

It is clear from the figures that target mass corrections remove the strong Q^2-dependence in the depression at $x > 0.6$, for low Q^2, and have no appreciable consequences in the intermediate x range. They also emphasize that the main contribution to the nuclear effect in the deuteron seems to be closely connected with the well known antishadowing of nuclear deep inelastic data.

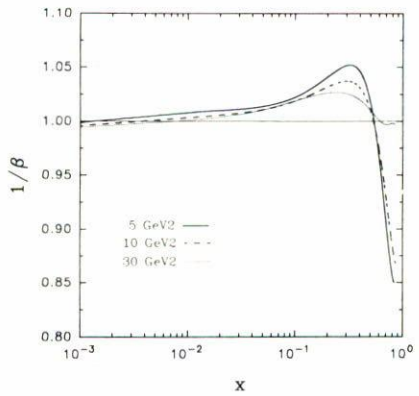

FIGURE 3. The same as Fig. 1 with target mass corrections.

The above mentioned parametrizations for the structure functions fit data at very low x values; for that reason we show our results in that region. Notice that the extrapolation to low x values is in agreement with a recent calculation of shadowing in lepton deuteron scattering [19].

In the NMC analysis, the Q^2–dependence of the ratio $F_2^n/F_2^p|_{\rm NMC}$ is extracted by fitting the data with a linear function of $\ln(Q^2)$ for each x bin, namely

$$\left.\frac{F_2^n}{F_2^p}(x_i,Q^2)\right|_{\rm NMC} = a(x_i) + b(x_i)\ln(Q^2). \tag{21}$$

Significant negative slopes in the x range 0.1 – 0.4 are found. The discrepancy between these slopes and the expectation of perturbative QCD [26] (see Fig. 4a) was interpreted in terms of higher twist effects. However, we find that the difference can be perfectly explained in terms of the same nuclear effects in the extraction of the neutron structure function that spoiled the Gottfried sum rule test and were parametrized in the first section.

The effective enhancement of the neutron structure function, which has been shown to be a decreasing function of Q^2, causes the slope to be more negative in the intermediate x range than it should be, and has the opposite effect where shadowing dominates. Figure 4b shows the slopes when the neutron to proton ratio is corrected with our parametrization of nuclear effects,

$$\frac{F_2^n}{F_2^p} = \beta\left[\left.\frac{F_2^n}{F_2^p}\right|_{\rm NMC} + 1\right] - 1, \tag{22}$$

and refitted for each x bin. The error bars represent statistical and systematic uncertainties added in quadrature. Once nuclear corrections are made, no much room is left for significative higher twist contributions in the intermediate x range.

Notice that, although the corrections to the naive expression $F_2^D = \frac{1}{2}[F_2^p + F_2^n]$ are small related to F_2^D, and have a rather circumspect dependence in energy, they strongly distort the extraction of higher twist terms.

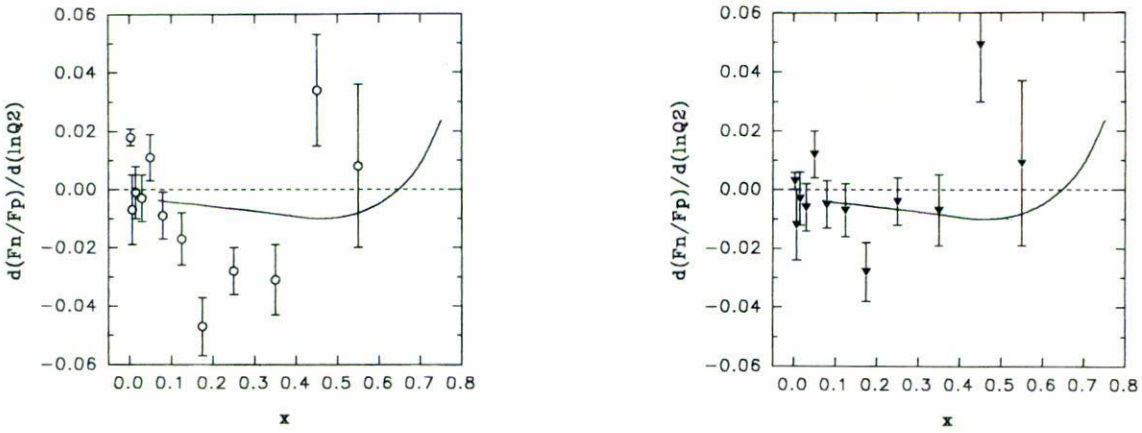

FIGURE 4. a) The derivative $d(F_2^n/F_2^p|_{\mathrm{NMC}})/d(\ln Q^2)$. The curve gives a result of a QCD calculation. b) The same as a) for the corrected ratio.

6. THE PIONIC CONTRIBUTION TO THE DEUTERON STRUCTURE FUNCTION

In this section we show how a very simple model based on the pionic content of the deuteron reproduces the main features of the nuclear effect.

Let us first recall the origin of the simple-minded expression (3). If the deuteron consists of *only* a proton and a neutron, and if we ignore shadowing, then one has

$$2F_2^D(x) = \int_x^2 dy \left[F_2^p\left(\frac{x}{y}\right) f_{p/D}(y) + F_2^n\left(\frac{x}{y}\right) f_{n/D}(y) \right], \tag{23}$$

where $f_{p/D}(y)$ is the number density of protons in the deuteron whose momentum is a fraction $y/2$ of the momentum of the deuteron. As usual, x for the deuteron is defined by

$$x = \frac{2Q^2}{2P \cdot q}, \tag{24}$$

where P is the deuteron 4-momentum. Then, in principle x can run between 0 and 2.

Isospin invariance gives

$$f_{n/D}(y) = f_{p/D}(y) \tag{25}$$

and charge conservation implies

$$1 = \int_0^2 dy\, f_{p/D}(y). \tag{26}$$

Now, in the simplest possible picture both, the proton and the neutron carry exactly one half of the momentum of the deuteron, so that

$$f_{p/D}(y) = \delta(1 - y). \tag{27}$$

Insertion of this in Eq. (24) yields Eq. (21), or more correctly

$$2F_2^D(x) = \begin{cases} F_2^p(x) + F_2^n(x), & x \leq 1, \\ 0, & x > 1. \end{cases} \tag{28}$$

Many arguments have been given against the pionic content of nuclei being negligible [27,28]. Let us therefore suppose that the deuteron wave-function contains a pionic component. In that case, ignoring shadowing, Eq. (23) is replaced by

$$2F_2^D(x) = \int_x^2 dy \left[F_2^p\left(\frac{x}{y}\right) + F_2^n\left(\frac{x}{y}\right)\right] f_{p/D}(y) + 3\int_x^2 dy\, F_2^\pi\left(\frac{x}{y}\right) f_{\pi/D}(y), \tag{29}$$

where

$$F_2^\pi(z) \equiv \tfrac{1}{3}\left[F_2^{\pi^+}(z) + F_2^{\pi^0}(z) + F_2^{\pi^-}(z)\right] \tag{30}$$

is the average pion structure function. In Eq. (29) we have, via isospin invariance, taken the number density of pions, whose momentum is $\frac{y}{2}$ of the deuteron momentum, as:

$$f_{\pi^+/D} = f_{\pi^0/D} = f_{\pi^-/D} \equiv f_{\pi/D}. \tag{31}$$

Baryon number conservation implies that Eq. (26) is unchanged, but momentum conservation now requires

$$1 = \int_0^2 dy\, \frac{y}{2}\left[2f_{p/D}(y) + 3f_{\pi/D}(y)\right]. \tag{32}$$

In the spirit of the simple picture that led to Eq. (3) let us now assume that the proton and neutron each carry exactly $\frac{1}{2}(1 - \epsilon)$ of the deuteron's momentum, so that Eq. (27) is replaced by

$$f_{p/D}(y) = \delta(1 - \epsilon - y). \tag{33}$$

Using this in Eqs. (32) and (26), one has, as expected

$$\int_0^2 dy\, \frac{y}{2}\left[3f_{\pi/D}(y)\right] = \epsilon, \tag{34}$$

i.e., ϵ is the fraction of the deuteron's momentum carried by its pionic constituents, and is expected to be very small.

Substitution of Eq. (33) in Eq. (29) yields

$$2F_2^D(x) = \left[F_2^p\left(\frac{x}{1-\epsilon}\right) + F_2^n\left(\frac{x}{1-\epsilon}\right)\right]\theta(1-\epsilon-x) + 3\int_0^2 dy\, F_2^\pi\left(\frac{x}{y}\right) f_{\pi/D}(y). \quad (35)$$

Since our primary aim is to learn about $F_2^p(x) - F_2^n(x)$, let us now write

$$\begin{aligned} F_2^p(x) - F_2^n(x) &= \left[2F_2^p(x) - 2F_2^D(x)\right] + \left[2F_2^D(x) - F_2^p(x) - F_2^n(x)\right] \\ &\equiv \left[2F_2^p(x) - 2F_2^D(x)\right] + \delta F_2^D(x). \end{aligned} \quad (36)$$

The first term of the R.H.S. of Eq. (36) is what is measured in the NMC experiment. The term $\delta F_2^D(x)$ is the correction needed to extract $F_2^p(x) - F_2^n(x)$.

From Eqs. (36) and (35) we see that

$$\begin{aligned} \delta F_2^D(x) &= \left[F_2^p\left(\frac{x}{1-\epsilon}\right) + F_2^n\left(\frac{x}{1-\epsilon}\right)\right]\theta(1-\epsilon-x) \\ &\quad - \left[F_2^p(x) + F_2^n(x)\right]\theta(1-x) + 3\int_x^2 dy\, F_2^\pi\left(\frac{x}{y}\right) f_{\pi/D}(y) \\ &\simeq \epsilon x\left[\frac{dF_2^p}{dx} + \frac{dF_2^n}{dx}\right]\theta(1-x) + 3\int_x^2 dy\, F_2^\pi\left(\frac{x}{y}\right) f_{\pi/D}(y). \end{aligned} \quad (37)$$

We shall now attempt to estimate the terms on the R.H.S. of Eq. (37). Since we are dealing with a small correction it should be safe to take dF_2^n/dx from the naive expression

$$F_2^n(x) = \left[2\frac{F_2^D(x)}{F_2^p(x)} - 1\right] F_2^p(x), \quad (38)$$

using NMC's parametrization for the ratio [14] and the one given in Ref. [15] for the proton structure function. The pion structure function is supposed to be known from experiment. We take for it the parametrization given in Ref. [29].

We do not have very convincing evidences for the shape of the pion distribution in the deuteron, so apart from a slight modification we follow the estimate of Berger *et al.* [30] and take*

$$3f_{\pi/D}(y) = \frac{\epsilon}{2}\frac{\Gamma(a+b+3)}{\Gamma(a+2)\Gamma(b+1)}\left(\frac{y}{2}\right)^a\left(1-\frac{y}{2}\right)^b, \qquad 0 \le y \le 2, \quad (39)$$

which is designed to satisfy Eq. (34). We fix $a = 1$, $b = 3$ as reasonable estimates.

The whole of the R.H.S. of Eq. (37) is then proportional to ϵ and this is the only free parameter. Models suggest that ϵ cannot be larger than a few percent. Let us therefore

*In our notation $3f_{\pi/D}$ corresponds to $f_{\pi/D}$ in Ref. [30].

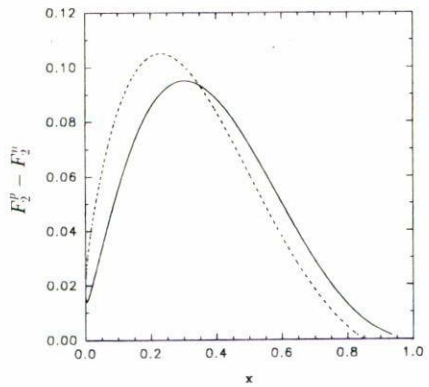

FIGURE 5. Values for the difference between the proton and neutron structure functions, Eq. (36), ($\epsilon = 0$ continuous line, $\epsilon = 0.05$ dashes).

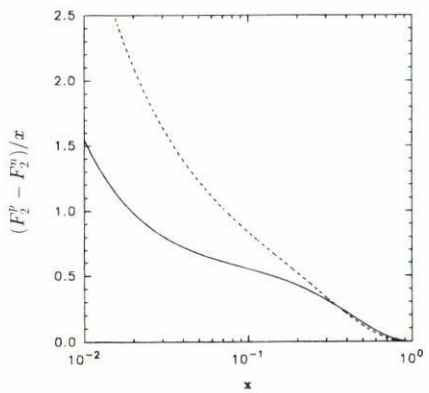

FIGURE 6. The same differences divided by x.

take $\epsilon = 5\%$ and see whether $\delta F_2^D(x)$ has a significant effect in Eq. (36). In Fig. 5 we show values of

$$\left[F_2^p(x) - F_2^n(x)\right]_{\text{naive}} \equiv F_2^p(x)\left[1 - \frac{F_2^n(x)}{F_2^p(x)}\right] \tag{40}$$

from the previously mentioned parametrizations and the result of adding $\delta F_2^D(x)$ to these. In Fig. 6 we show the integrand of the Gottfried sum rule, *i.e.*, the same functions divided by x. We are assuming the convergence of the Gottfried sum rule, so we extrapolate the R.H.S. of Eq. (36) to zero at $x = 0$. It is seen that even with ϵ of just 1% there is a non-trivial modification at small values of x.

In order to compare this model prediction with the extraction of the first section, we present in Fig. 7 the $1/\beta$ function calculated for different Q^2–values.

Figure 7 shows how this simple model reproduces the main features of the nuclear effect, providing the magnitude, x- and Q^2–dependence of the nuclear effect in a very good approximation, with only one free parameter: the fraction of the deuteron momentum carried by its pionic constituents.

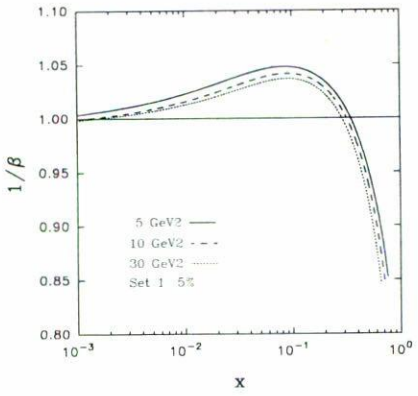

FIGURE 7. The pionic model prediction for the $1/\beta_D$-function.

This approximation does not include contributions from other mesons as we expect the relevant meson effects in deep inelastic scattering to be associated with pion exchange. Fermi motion effects, which are expected to enhance the deuteron structure function as $x \to 1$, are negligible in the low and intermediate x–range we are interested in.

It is worth noticing that in this simple model the positive and negative contributions to the deuteron structure function which give rise to nuclear antishadowing and shadowing respectively are clearly identified. The former, related to the scattering off pions, dominates at not too small values of x and is compensated as $x \to 0$ by the latter, which is produced by the nucleon's loss of momentum. Both contributions grow as $x \to 0$ but there is a tiny residual shadowing effect resulting from their interplay.

At $x \sim 0.3$ the Q^2–dependence of the effect seems to be even stronger than the one predicted by the model. There are no parameters in the model to fine tune this difference; however, as we have said, this model does not pretend to be a complete description for the deuteron.

7. PARTON FUSION EFFECTS AND SHADOWING

In the above analysis we have neglected shadowing and the possibility that from different nucleons in the dense cloud of small–x partons fusion may take place between partons. In the latter case, an additional contribution to the deuteron structure function, ΔF_2^D, related to an intrinsic distortion of the nucleon ones in the nuclear medium, is expected.

Close, Qiu and Roberts [31] have estimated the correction $\Delta F_2^A(x)$ per nucleon arising from parton fusion for $A = 56$. In their calculation of fusion processes with no final state partons, initial state recombination, they found dominant those involving two partons from two different nucleons. Their result depends slightly on model assumptions at the extent to which partons leak out of the nucleon and the input parton distributions. An overall $A^{1/3}$ behaviour is deduced using an approximation for small x and large A.

Because the deuteron is a very loosely bound large structure, the effects coming from the proximity of the nucleons to each other will be smaller than expected on the basis of the $A^{1/3}$ behaviour of $\Delta F_2^A(x)$. A naive $A^{1/3}$ scaling extrapolation gives for the deuteron

$\Delta F_2^D \approx \frac{1}{3}\Delta F_2^{56}$ whereas estimates based on a more realistic deuteron radius suggest an even smaller value. In that case, the values of ΔF_2^{56} given in Ref. [31], yields a correction to Eq. (37) of the same sign as δF_2^D which is small compared with δF_2^D for $x < 0.6$ and for reasonable values of ϵ.

An attempt to estimate shadowing in deuteron, based upon a mixture of vector dominance and parton fusion, has been made by Badelek and Kwiecinsky [19]. The correction term $\delta F_2^D|_{\text{shadowing}}$ found by them, negative for $x < 0.1$, is negligible compared with the positive pionic correction. However, it is comparable in magnitude with the pionic correction for $x \leq 0.01$.

8. CONCLUSIONS

We therefore conclude that significant tests for the neutron structure function cannot be made on the basis of the deuteron data without taking into account nuclear effects.

Although very small, these effects are amplified when the proton and the resulting structure function for the neutron are compared.

Our parametrization of these effects successfully accounts for the discrepancy with the quark-parton model observed in the verification of the Gottfried sum rule. The emerging picture for these effects seems to be a natural extrapolation of what is seen in heavier nuclei.

Sum rules weight differently the information extracted from nuclear targets allowing stringent consistency checks on these effects, as is the case in the first two examples analyzed. For the BSR our predictions are not as definite due to the lack of sufficient information, but warn us against eventual misleading interpretations in forthcoming experiments.

The unexpected Q^2–dependence observed in the NMC analysis of the F_2^n/F_2^p data, which deviates form the standard predictions of QCD, confirms our conclusions. Disregarding nuclear effects again, the relation between the proton and the neutron structure functions looks odd, particularly in the intermediate x range, where we found they were stronger. There, the discrepancy with QCD fades away when corrections are taken properly into account.

Model estimates based on the pionic content of the deuteron are consistent with this parametrization and seem to provide a satisfactory explanation for the unusual features of deep inelastic deuteron data.

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