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Spin-dependent twist-four matrix elements from g_1 data in the resonance region

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Matrix elements of spin-dependent twist-four operators are extracted from recent data on the spin-dependent g_1 structure function of the proton and deuteron in the resonance region. We emphasize the need to include the elastic contributions to the first moments of the structure functions at $Q^2 < 2 \text{ GeV}^2$. The coefficients of the $1/Q^2$ corrections to the Ellis-Jaffe sum rules are found to be 0.04 ± 0.02 and $0.03 \pm 0.04 \text{ GeV}^2$ for the proton and neutron, respectively. [S0556-2821(97)50113-5]

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There has been much activity in recent years surrounding various deep-inelastic spin sum rules, such as the Bjorken [1] and Ellis-Jaffe sum rules [2], which test our understanding of the spin structure of the nucleon, as well as our ability to calculate higher-order radiative corrections in QCD. An intriguing issue in the study of these sum rules at moderate values of the momentum transfer squared, Q^2 (say $Q^2 \sim 0.5$ to 3 GeV^2), is that of higher-twist corrections. In this paper, we extract the twist-four matrix elements from recent data taken by the E143 Collaboration at SLAC [3] on the proton and deuteron g_1 structure functions, and compare these with some recent theoretical estimates.

Higher-twist corrections to the polarized deep-inelastic sum rules were first studied by Shuryak and Vainshtein [4]. The coefficient functions were recalculated in Ref. [5] and confirmed in Refs. [6] and [7]. There is a long list of calculations and estimates of the nonperturbative higher-twist matrix elements in the literature [5,6,8–12]. The interplay between the perturbation series at high orders and higher-twist matrix elements was first discussed by Mueller in Ref. [13]. The question concerns the precise definition of higher-twist corrections, as these are related to the procedure of regularizing an asymptotic perturbation series. A concrete proposal of separating the perturbative and nonperturbative contributions was suggested in Ref. [14].

Very recently, the E143 Collaboration [3] published the first data on the first moments of the g_1 structure functions of the proton and neutron (the latter being extracted from deu-

terium data) in the resonance region (at $Q^2 = 0.5$ and 1.2 GeV^2). According to the phenomenon of parton-hadron duality, these data have a direct bearing on the size of the higher-twist matrix elements. From the successful phenomenology of the QCD sum rule method [15], power corrections in an operator product expansion (OPE) have direct control over the structure of the low-lying resonances. In fact, much work has appeared in the literature on the calcu-

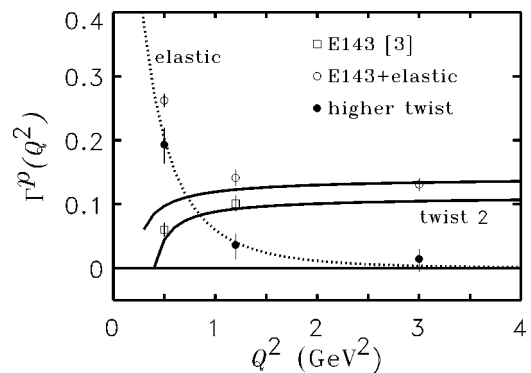


FIG. 1. Q^2 dependence of $\Gamma^p(Q^2)$. The two solid lines represent the upper and lower limits of the twist-two part of $\Gamma^p(Q^2)$, while the dotted curve is the elastic component, as parameterized in Ref. [21]. The squares denote the inelastic contribution extracted from the E143 experiment [3], the open circles include also the elastic piece, while the full circles are the pure higher-twist contributions.

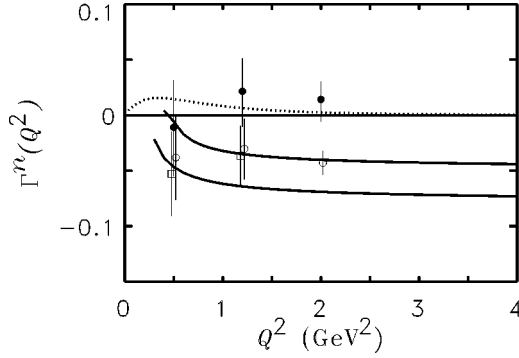


FIG. 2. Same as in Fig. 1, but for the neutron.

lation of low-energy hadronic observables in terms of vacuum condensates. Of course, the parton-hadron duality also allows determination of the same condensates from the resonance masses and widths, if these are known to sufficient accuracy. In our case, we shall employ the latter approach to duality: namely, resonances (including the nucleon elastic contribution) fix the higher-twist matrix elements. In the case of unpolarized deep-inelastic scattering, a similar analysis was performed in Ref. [16]. Here we shall use the newly measured data from Ref. [3] to extract the spin-dependent twist-four matrix elements.

The first moment of the g_1 structure function of the nucleon is defined as

$$\Gamma^N(Q^2) = \int_0^1 dx g_1^N(x, Q^2), \quad (1)$$

where $N=p$ or n , and the upper limit includes the nucleon elastic contribution. The inclusion of the elastic component is critical if one wishes to use the OPE to study the evolution of the sum rule in the moderate Q^2 region [17]. Note that the application of the OPE requires a product of two currents, which arises in deep-inelastic scattering only after summing over all final (including elastic) hadronic states. For unpolarized scattering, this point was emphasized some time ago by Ellis [18]. In Ref. [19], attempts were made to extract the twist-four matrix elements from the first moment of g_1 , without inclusion of the elastic contribution. In light of the logic behind the OPE, this procedure is clearly incorrect. Furthermore, the OPE is known to break down at low Q^2 ($Q^2 \lesssim 0.5$ GeV 2); hence the Drell-Hearn-Gerasimov sum rule [20] at $Q^2=0$ has no obvious bearing on the size of the twist-four contributions [5].

In Figs. 1 and 2 we show the first moments $\Gamma^p(Q^2)$ and $\Gamma^n(Q^2)$, respectively, at three different Q^2 values ($Q^2 \lesssim 3$ GeV 2) (the data are from Refs. [3,22,23]). The data, shown by the open circles, contain contributions from the measured x regions covered in the experiments, together with theoretical extrapolations into the unmeasured small- x region, and also from elastic scattering at $x=1$. Note that the neutron points are obtained from the deuteron and proton data assuming a small ($\sim 5\%$) D -state admixture in the deuteron. Compared with the proton data, the neutron results are much poorer, and could be significantly improved in future measurements at Jefferson Lab [24]. One should note that the contributions from the x -region covered by the recent E143 analysis [3] are not entirely model independent. A number of

assumptions have been made regarding the contributions of the g_2 structure function, the Δ resonance, etc. [3]. For the present analysis, however, we simply adopt the data as published in Ref. [3], keeping in mind that future experiments may help to clarify some of these assumptions.

For the small- x extrapolation, we use a recent parameterization from Ref. [25] fitted to the global polarized deep-inelastic scattering data, which respects the Bjorken sum rule [$g_A = 1.257$ and $\alpha_s^{\text{NLO}}(M_Z^2) = 0.117 \pm 0.005$]. The parameterization has been constructed at a scale $Q_0^2 = 1$ GeV 2 , and evolution to different Q^2 values has been done including the complete next-to-leading order (NLO) corrections [26]. At such small Q^2 values one might question the role of higher-twist contributions in any small- x extrapolation. However, previous experience from unpolarized deep-inelastic data tells us that higher-twist effects at small x tend to be rather small [27]. It is difficult to assign an error to the theoretical small- x extrapolation, as this is still a somewhat controversial, but interesting, subject which is currently under active study [28–32]. The data shown by the squares in Figs. 1 and 2 include only the inelastic contributions, as discussed above.

The dotted curves in Figs. 1 and 2 represent the elastic contributions to the Γ^N moments calculated in terms of nucleon form factors [5]:

$$\Gamma_{\text{el}}^N(Q^2) = \frac{1}{2} F_1^N(Q^2) [F_1^N(Q^2) + F_2^N(Q^2)], \quad (2)$$

where we have used the parametrization of $F_{1,2}^N(Q^2)$ from the fit of Ref. [21]. For the proton, the elastic contribution is negligible at $Q^2 > 3$ GeV 2 , and is about 10% of the inelastic at $Q^2 = 2$ GeV 2 . At $Q^2 = 1$ GeV 2 it is as important as the inelastic component, and below 0.5 GeV 2 the elastic contribution becomes dominant. For the neutron, the elastic contribution peaks around $Q^2 = 0.5$ GeV 2 , and becomes quite small above ≈ 1.5 GeV 2 and below ≈ 0.1 GeV 2 .

According to the OPE, in the limit of large $Q^2 \gg \Lambda_{\text{QCD}}^2$, $\Gamma^N(Q^2)$ can be calculated via the twist expansion:

$$\Gamma^N(Q^2) = \sum_{\tau=2,4,\dots} \frac{\mu_\tau^N(Q^2)}{Q^{\tau-2}}, \quad (3)$$

where μ_τ^N is related to nucleon matrix elements of operators of twist $\leq \tau$. From the total $\Gamma^N(Q^2)$ one can obtain the higher-twist component by subtracting the twist-two contribution, μ_2^N , which can be written as a series expansion in α_s : $\mu_2^N(Q^2) = \sum_n C_n^N \alpha_s^n(Q^2)$. It is suspected that the coefficients C_n^N grow like $n!$ as $n \rightarrow \infty$, and therefore, strictly speaking, μ_2^N is not a well-defined quantity [13]. The uncertainty in regularizing the divergent series is closely related to the precise definition of the higher-twist contributions. In this paper we maximally utilize the available perturbative calculations up to $O(\alpha_s^3)$ [33], and define μ_2^N up to this order as the entire twist-two contribution. We will return to this point later. For three quark flavors, the three-loop result for the twist-two component of the proton and neutron first moments is given by [33]

$$\begin{aligned} \mu_2^{p(n)}(Q^2) = & \left[1 - \left(\frac{\alpha_s}{\pi} \right) - 3.5833 \left(\frac{\alpha_s}{\pi} \right)^2 - 20.2153 \left(\frac{\alpha_s}{\pi} \right)^3 \right] \left(\pm \frac{1}{12} g_A + \frac{1}{36} a_8 \right) \\ & + \left[1 - 0.3333 \left(\frac{\alpha_s}{\pi} \right) - 0.54959 \left(\frac{\alpha_s}{\pi} \right)^2 - 4.44725 \left(\frac{\alpha_s}{\pi} \right)^3 \right] \frac{1}{9} \Sigma_{\text{inv}}, \end{aligned} \quad (4)$$

where the \pm refers to p or n . The leading-twist component in Eq. (4) is given in terms of the triplet and octet axial charges, g_A and a_8 , respectively, and the quantity Σ_{inv} , defined as the renormalization group-invariant nucleon matrix element of the singlet axial current [33], $\Sigma_{\text{inv}} \equiv \Sigma(Q^2 = \infty)$. With the above value of g_A , the leading-twist contribution (4) is calculated with the values $a_8 = 0.579 \pm 0.025$ [31], extracted from weak hyperon decays, and $\Sigma_{\text{inv}} \approx 0.15 \pm 0.12$ obtained from the global fit of Ref. [25]. The results for the proton and neutron are shown in Figs. 1 and 2 by the solid curves, where the band range reflects the combined error in Σ_{inv} and α_s . For the latter we have taken $\alpha_s^{\text{NLO}}(1 \text{ GeV}^2) = 0.45 \pm 0.05$ [34]. Subtracting from the open circles in Figs. 1 and 2 the leading-twist component, one obtains the pure higher-twist contribution, denoted by the full circles. Note that the increased error bars on the higher-twist points simply reflect the uncertainty in $\mu_2^N(Q^2)$. Thus the higher-twist contribution and the uncertainty in α_s are correlated at intermediate values of Q^2 ($0.5 \leq Q^2 \leq 2 \text{ GeV}^2$). The higher-twist contribution can thus be reliably extracted only when α_s is more accurately determined from other sources.

Turning now to the higher-twist contributions to $\Gamma^N(Q^2)$, the $1/Q^2$ term in Eq. (3) is a sum of three terms:

$$\mu_4^N(Q^2) = \frac{1}{9} M^2 [a_2^N(Q^2) + 4d_2^N(Q^2) - 4f_2^N(Q^2)]. \quad (5)$$

The a_2^N component, being given by the second moment of the twist-two part of the polarized g_1^N structure function,

$$a_2^N(Q^2) = 2 \int_0^1 dx x^2 g_1^N(x, Q^2), \quad (6)$$

arises from the target mass correction [5], and can be evaluated straightforwardly from global parameterizations of the leading-twist part of $g_1^N(x, Q^2)$. The twist-three correction in Eq. (5) can be extracted from the leading-twist contributions to the following moment of the g_1^N and g_2^N structure functions:

$$d_2^N(Q^2) = \int_0^1 dx x^2 [2g_1^N(x, Q^2) + 3g_2^N(x, Q^2)]. \quad (7)$$

Recently the d_2 coefficients of the proton and deuteron have been determined in Ref. [35] at an average value of $Q^2 = 5 \text{ GeV}^2$, with the results: $d_2^p = 0.0054 \pm 0.0050$, and $d_2^D = 0.0039 \pm 0.0092$. To a good approximation the neutron d_2^n can be obtained from the relation: $d_2^n = 2d_2^D / (1 - 3/2\omega_D) - d_2^p$, where ω_D is the deuteron D -state probability (more sophisticated treatments [36] which account for binding and Fermi motion effects give small corrections in comparison with the present error bars). With $\omega_D = 5\%$, this

gives $d_2^n = 0.0030 \pm 0.020$ at $Q^2 = 5 \text{ GeV}^2$. Without any D -state correction [37] the value would be around 25% smaller. To obtain d_2 at a different Q^2 one can use the leading logarithmic evolution as computed in Refs. [4,38]. In principle, the anomalous dimensions for the singlet and non-singlet components differ, so that one would require separate knowledge of the singlet and nonsinglet matrix elements to perform the evolution. In practice, however, for 3 flavors the one-loop singlet and nonsinglet anomalous dimensions turn out to be very similar [4,38], and at the present level of accuracy the differences can be safely ignored.

Lastly, the twist-four contribution, f_2^N , to μ_4^N is defined by the matrix element

$$2f_2^N(Q^2) M^2 S^\mu = \sum_f e_f^2 \langle P, S | g \bar{\psi}_f \tilde{F}^{\mu\nu} \gamma_\nu \psi_f | P, S \rangle, \quad (8)$$

where S^μ is the nucleon spin vector, and the gluon field-strength tensor is $\tilde{F}^{\mu\nu} = (1/2)\epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta}$, with $\epsilon^{0123} = +1$, and g appears in the covariant derivative as $D^\mu = \partial^\mu + igA^\mu$.

In the remainder of this paper, our focus will be on the extraction of this matrix element from the data in Figs. 1 and 2. To achieve this, one must first subtract the leading-twist, target mass, and the twist-three contributions from the $\Gamma^N(Q^2)$ data, and define

$$\begin{aligned} \Delta\Gamma^N(Q^2) \equiv & \Gamma^N(Q^2) - \mu_2^N(Q^2) - \frac{1}{9} \frac{M^2}{Q^2} \\ & \times [a_2^N(Q^2) + 4d_2^N(Q^2)]. \end{aligned} \quad (9)$$

In Figs. 3 and 4 the extracted $\Delta\Gamma^N(Q^2)$ values for the proton and neutron are shown, respectively, as a function of $1/Q^2$.

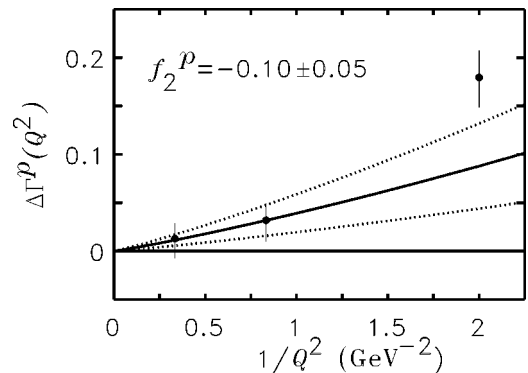


FIG. 3. The $1/Q^2$ dependence of the higher-twist contribution $\Delta\Gamma^p(Q^2)$ defined in Eqs. (9) and (10). The curves correspond to $f_2^p = -0.10 \pm 0.05$ at $Q^2 = 1 \text{ GeV}^2$ (the solid represents the central value, while the dotted curves indicate the error range on f_2^p).

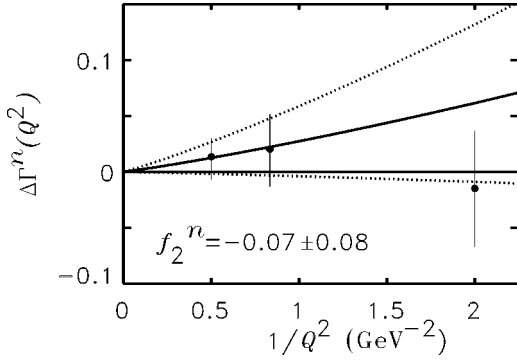


FIG. 4. Same as in Fig. 2 but for the neutron. The curves correspond to $f_2^n = -0.07 \pm 0.08$ at $Q^2 = 1 \text{ GeV}^2$.

Theoretically, the data in Figs. 3 and 4 represent contributions from $f_2^N(Q^2)$, as well as from $\tau=6$ and higher twists:

$$\Delta\Gamma^N(Q^2) = -\frac{4}{9} \frac{M^2}{Q^2} f_2^N(Q^2) + \sum_{\tau=6,8,\dots} \frac{\mu_\tau^N}{Q^{\tau-2}}. \quad (10)$$

The twist expansion is believed, however, to be controlled by a scale related to the average transverse momentum of quarks in the nucleon [39], typically of the order 0.4–0.5 GeV [5,39]. Therefore one can reasonably expect that the role of $\tau \geq 6$ effects should not be significant for $Q^2 > 1 \text{ GeV}^2$, and not overwhelming for $Q^2 \geq 0.5 \text{ GeV}^2$.

Finally, the matrix elements f_2^N can be extracted from the data points in Figs. 3 and 4 at $Q^2 > 1 \text{ GeV}^2$ by neglecting the higher-twist terms in Eq. (10). The Q^2 evolution of $f_2^N(Q^2)$ is also taken into account at leading logarithmic order [4,38]. This logarithmic Q^2 dependence results in the slight deviations in the curves in Figs. 2 and 3 from linearity. At a scale of $Q^2 = 1 \text{ GeV}^2$ we find:

$$f_2^p = -0.10 \pm 0.05, \quad (11)$$

$$f_2^n = -0.07 \pm 0.08. \quad (12)$$

The effects of higher-order [$O(\alpha_s^4)$ and beyond] terms in the coefficient functions of the twist-two contributions in Eq. (4) may be estimated using the method of Padé approximants [40]. Using the “[1/2]” approximants [41] for both the non-singlet and singlet components, the central value of f_2^p is found to decrease from -0.10 to ≈ -0.17 , while for the neutron it increases slightly, from -0.07 to ≈ -0.06 . We should note, however, that the reliability of the Padé approximants method in the region $Q^2 \leq 1.5 \text{ GeV}^2$ may be questionable, since there the differences between the exact $O(\alpha_s^3)$ calculation in Eq. (4) and its Padé approximation are quite significant.

Including the a_2^N and d_2^N contributions, one can finally determine the $1/Q^2$ correction to the Ellis-Jaffe sum rules:

$$\mu_4^p = (0.04 \pm 0.02) \text{ GeV}^2, \quad (13)$$

$$\mu_4^n = (0.03 \pm 0.04) \text{ GeV}^2, \quad (14)$$

at the scale $Q^2 = 1 \text{ GeV}^2$.

The central values in Eqs. (11) and (12) seem to suggest that the isoscalar combination of the twist-four matrix elements is much larger than the isovector combination. One might suspect therefore that the singlet twist-two contribution to the sum rule obtained from the global fit [25] is too small. To investigate the effect that a larger value of Σ_{inv} would have on the twist-four matrix elements, we have re-analyzed the data using $\Sigma_{\text{inv}} \approx 0.3$ as the central value [32]. The effect is a reduction of f_2^p to ≈ -0.05 , and f_2^n to ≈ 0.0 , which would then lead to similar values for both the isotriplet and isosinglet combinations. Of course these values are still consistent with the results in Eqs. (11) and (12) within the errors. In principle, one could eliminate the dependence on Σ_{inv} by considering only the isovector combination $\Gamma^p - \Gamma^n$, thereby reducing significantly the uncertainty in the isovector twist-four matrix element. Unfortunately, the error associated with the neutron data is largely experimental, so that the final proton–neutron moment would have an error which is as large as that for the neutron points in Fig. 4.

The values determined in Eqs. (11) and (12) can be compared with several model calculations of the twist-four matrix elements in the literature. The first estimates of f_2^N were made using QCD sum rules. The result from Ref. [6] is $f_2^p = 0.050 \pm 0.034$ and $f_2^n = -0.018 \pm 0.017$, while that from Ref. [11] is $f_2^p = 0.037 \pm 0.006$ and $f_2^n = 0.013 \pm 0.006$. Alternative estimates of the $\tau=4$ matrix elements were made using the MIT bag model [5,42]. The result there, evolved from the bag scale up to $Q^2 \sim 1 \text{ GeV}^2$, was found to be $f_2^p = -0.028$ and $f_2^n = 0$.

The results obtained in this work will be improved as more experimental information becomes available in future. The error on the data points in Figs. 3 and 4 come mainly from the uncertainty associated with the value of α_s , and the singlet axial charge Σ_{inv} , when subtracting the twist-two contribution from the total $\Gamma^N(Q^2)$. Therefore better knowledge of the twist-two part of the structure function at higher Q^2 , and a more accurate determination of α_s from other experiments, will be valuable in pinning down the higher-twists at low Q^2 . Certainly more data points are needed in order to establish a clearer trend of the Q^2 dependence at moderate values of Q^2 ($Q^2 \sim 0.5\text{--}3.0 \text{ GeV}^2$). In particular, the neutron data points are irregular and should be confirmed in subsequent experiments. In this respect, future experiments at Jefferson Lab and other facilities can contribute much to our present understanding of the twist-four matrix elements of the nucleon.

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