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W.-D.Nowak*, A.V.Sidorov, M.V.Tokarev

ON A POSSIBILITY TO DETERMINE THE SIGN OF THE POLARIZED GLUON DISTRIBUTION

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Новак В.-Д., Сидоров А.В., Токарев М.В. E2-96-315

О возможности определения знака спин-зависимой функции распределения глюонов

Изучается возможность получения информации о знаке спин-зависимой функции распределения глюонов $\Delta G(x,Q^2)$ из имеющихся данных по глубоконеупругому рассеянию. В анализе используется феноменологическая процедура построения спин-зависимых партонных распределений Δu_v, Δd_v, $\Delta\bar{u}$, $\Delta\bar{d}$, Δs и ΔG, учитывающая знаки валентных и морских партонных распределений. Выбор последних мотивирован механизмом т'Хоофта для кварк-кваркового взаимодействия, индуцированного инстантонами. Процедура учитывает также аксиальную глюонную аномалию и данные о вкладе кварков в спин протона $\Delta\tilde{u}$, $\Delta\tilde{d}$ и $\Delta\tilde{s}$. Предсказания для зависимости структурных функций g_1^p, g_1^n от x и Q^2 сравниваются с экспериментальными данными. Показано, что нейтронная структурная функция g_1^n особенно чувствительна к знаку $\Delta G(x,Q^2)$. Результаты нашего анализа поддерживают вывод о положительном знаке глюонной функции распределения ΔG.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Nowak W.-D., Sidorov A.V., Tokarev M.V. E2-96-315

On a Possibility to Determine the Sign of the Polarized Gluon Distribution

We investigate the possibility to draw conclusions on the sign of the spin-dependent gluon distribution, $\Delta G(x,Q^2)$, from existing polarized DIS data. The spin-dependent parton distributions Δu_v, Δd_v, $\Delta\bar{u}$, $\Delta\bar{d}$, Δs, and ΔG are constructed in the framework of a phenomenological procedure taking into account some assumptions on signs of valence and sea parton distributions motivated by 't Hooft's mechanism of quark-quark interaction induced by instantons. The axial gluon anomaly and data on integral quark contributions to the proton spin, $\Delta\tilde{u}$, $\Delta\tilde{d}$, and $\Delta\tilde{s}$, are also taken into account. Predictions for the x- and Q^2-dependencies of the polarized proton and neutron structure functions, g_1^p and g_1^n, are compared to experimental data. It is shown that the neutron structure function, g_1^n, is especially sensitive to the sign of $\Delta G(x,Q^2)$. The results of our analysis supports the conclusion that this sign should be positive.

The investigation has been performed at the Laboratory of High Energies, JINR.

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1 Introduction

Parton distributions in the nucleon are of universal nature, hence their parametrizations obtained from deep inelastic lepton-nucleon scattering can be utilized for simulations of processes outside lepton nucleon scattering; the polarized parton distributions are especially useful to predict the behaviour of pp interactions with polarized proton beams to facilitate future research programs at the RHIC, HERA and LHC colliders.

Recent results deep inelastic lepton-nucleon scattering experiments at SLAC [1, 2] and CERN [3] on spin-dependent structure functions for proton and deuteron targets, g_1^p and g_1^d, stimulate the interest in determining the spin-dependent gluon and quark distributions in a polarized nucleon. Since a complete solution of this problem is beyond the scope of perturbative QCD and there are still no sufficiently precise non-perturbative calculations available, the usual procedure is to fit numerous parametrizations of both spin-independent and spin-dependent parton distributions to the data. Up to now there is no unique solution; the results depend in one or the other way on the method used.

Polarized parton distributions can be extracted in an indirect manner from doubly polarized deep inelastic lepton-proton and lepton-deuteron scattering; the measurable observables are the asymmetries A^p and A^d. The structure function g_1^p can be extracted from A^p according to

$$g_1^p(x,Q^2) = A^p(x,Q^2) \cdot \frac{F_2^p(x,Q^2)}{2x(1+R(x,Q^2))}, \qquad (1)$$

where additional information on the unpolarized structure function F_2^p [4] and on the ratio of longitudinal to transverse photon cross section $R(x,Q^2) = \sigma_L/\sigma_T$ [5] are required. The deuteron structure function is determined in a similar way taking into account appropriate nuclear corrections.

Since there is no practical way at present to directly extract polarized parton distributions from experimental data it is important to develop flexible procedures to construct these distributions incorporating relevant features of the data as well as reasonable constraints derived from our present theoretical understanding of the nucleon.

At present there is no strong argument favouring a positive or negative sign of the spin-dependent gluon distribution, $\Delta G(x,Q^2)$. Several sets of spin-dependent parton distributions were constructed utilizing rather different approaches [6, 7, 8, 9] mostly assuming a positive sign of ΔG. Different parameter choices leading to a different behaviour of ΔG at $x \to 1$ ($G\uparrow \sim G\downarrow$, $G\uparrow \gg G\downarrow$, $G\uparrow \ll G\downarrow$) were studied in [10]. Both positive and negative values of the sign of ΔG over a wide kinematical range $10^{-3} < x < 1$ were considered in [9]. A detailed NLO QCD analysis of the proton and deuteron data on g_1 was performed in [8] concluding that the size of the gluon distribution drives the perturbative evolution and, due to the fact that the SMC and E143 data were taken at different values of Q^2, the polarized gluon distribution turned out to be large and positive.

The aim of the present paper is to separate experimental observables being sufficiently sensitive to allow a determination of the sign of ΔG. As we shall show later, the neutron structure function g_1^n seems to be one of those observables.

To construct the spin-dependent parton distributions a phenomenological method proposed in [9] is used. This method incorporates some constraints on shape and sign of parton distributions, it utilizes results on the quark contributions to the nucleon spin obtained in other analyses, and the effect of the axial anomaly is taken into account. We study the x and Q^2 dependence of $g_1^n(x,Q^2)$ for two different scenarios: $\Delta G > 0$ and $\Delta G < 0$. The calculated predictions are compared to experimental data; a χ^2 criterion is chosen to judge in which of the two scenarios theoretical curves are better describing the experimental data on $g_1^n(x,Q^2)$. Eventually, the choice for a positive sign of ΔG will turn out to be the more likely one, i.e. the polarized structure function of the neutron will be shown to be sensitive to the sign of ΔG.

2 Method

The spin-dependent proton structure function g_1^p is expressed through spin-dependent parton distributions in a simple way

$$g_1^p(x,Q^2) = \frac{1}{2} \cdot \{\frac{4}{9}\Delta\tilde{u}(x,Q^2) + \frac{1}{9}\Delta\tilde{d}(x,Q^2) + \frac{1}{9}\Delta\tilde{s}(x,Q^2)\}, \qquad (2)$$

where $\Delta q_f = q_f^+ - q_f^-$, and the $q_f^\pm$ are the probability distributions to find a quark having positive (+) or negative (−) helicity relatively to positive proton helicity. The neutron structure function $g_1^n(x,Q^2)$ can be written in a similar form using the replacement $\Delta\tilde{u} \leftrightarrow \Delta\tilde{d}$. The valence distributions $\Delta q_v, \Delta q_v$ are then obtained from $\Delta q_v = \Delta q - 2\Delta\bar{q}$. Since in this paper we shall use the spin-dependent parton distributions constructed in [9] we briefly describe in the following sections the main features of the applied method.

2.1 Shape of Parton Distributions

For the general form of a spin-dependent parton distribution Δq_f we use

$$\Delta q_f = sign(q_f) \cdot x^{\alpha_f} \cdot (1-x)^{\beta_f} \cdot q_f, \quad q_f = u_v, d_v, \bar{u}, \bar{d}, s, G. \qquad (3)$$

Here q_f is the spin-independent parton distribution, α_f, β_f are free parameters which are to be found by comparison with experimental data. From the restriction

$$|\Delta q_f| < q_f \qquad (4)$$

follows that both probability distributions q_f^+, q_f^- as well as their sum $q_f = q_f^+ + q_f^-$ need to be positive; moreover β_f should not be negative. To avoid the latter constraint we introduce a renormalised parton distribution $q_f^R = (1-x)^{\beta_f} \cdot q_f$. This leads to the following general form of a spin-dependent parton distribution

$$\Delta q_f = sign(q_f) \cdot x^{\alpha_f} \cdot q_f^R. \qquad (5)$$

We note that since all presently available procedures to construct both spin-independent and spin-dependent distributions do imply fitting procedures and have consequently no

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unique solution. Hence we believe that at present it is recommended to incorporate general restrictions on Δq_f like the one above; this makes it easier to develop flexible schemes to construct the helicity parton distributions q_f^+ and q_f^-, separately.

2.2 Signs of Parton Distributions

Up to now there exists neither a running experiment to directly measure the polarized gluon distribution nor does the variety of indirect analyses give a unique result. Hence there exist no strong arguments on the sign of ΔG. Our approach will be to allow for both signs of ΔG and compare the quality of our model-dependent predictions to the experimental data.

We note that a direct access to ΔG will be possible in future experiments. Utilizing polarized protons at RHIC for the (approved) experiments STAR and PHENIX [11] and, possibly, for the suggested internal polarized target experiment *HERA-$\vec{N}$* [12] at HERA, the measurement of ΔG seems feasible in the range $0.1 \leq x_{gluon} \leq 0.35$. Also new doubly polarized lepton-nucleon scattering experiments proposed at CERN [13] and suggested at SLAC [14, 15] might contribute very valuable information on ΔG.

For valence quark distributions the situation is much better defined; we take the sign of Δu_v as positive and that of Δd_v as negative, respectively. This choice is motivated by the fact that the dominant configuration in the proton wave function is $u(\uparrow)u(\uparrow)d(\downarrow)$, here the arrow denotes the quark spin direction. The same choice is made in most analyses of experimental data on quark contributions to the proton spin [1, 2, 3], [16]-[19].

We assume for signs of $\Delta\bar{u}$ ($\Delta\bar{d}$) to be positive (negative). This is motivated by 't Hooft's mechanism [20] for the spin configuration $u(\uparrow)u(\uparrow)d(\downarrow)$ which determines the dynamics of quark helicity flips. The incoming left helicity quark $q_L = (1+\gamma_5)q/2$ scattered from zero modes in the instanton field leads to an outgoing right helicity quark $q_R = (1-\gamma_5)q/2$. Effective Lagrangians are constructed in [21]; in the particular case of $N_f = 2$ flavours it can be written as

$$L = \int d\rho \cdot n(\rho)(\frac{4}{3}\pi^2\rho^3)^2\{\bar{u}_R u_L \bar{d}_R d_L[1 + \frac{3}{32}(1 - \frac{3}{4}\sigma^u_{\mu\nu}\sigma^d_{\mu\nu})\lambda^a_u\lambda^a_d] + (R \leftrightarrow L)\}. \quad (6)$$

Here ρ is the size of instanton, $n(\rho)$ is the instanton density, $\sigma_{\mu\nu} = i/4\cdot(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)$, and λ^a are matrixes for $SU_c(3)$ group. Once the left helicity quark scatters off an instanton it becomes a right helicity one and a $q_R\bar{q}_R$ pair is created; the helicity of the sea quarks being opposite to that of the initial quark. In other words, the spin flip of the valence quarks u^+ and d^- determines the sign of the corresponding sea quark distributions - negative for $\Delta\bar{d}$ and positive for $\Delta\bar{u}$. A negative sign of Δs is in agreement with the arguments mentioned above and is supported by the results of several analyses of g_1^p data [1, 2, 3], [16]-[19].

2.3 Inclusion of Axial Anomaly

It was shown in [22] that the flavour-singlet axial current

$$A^0_\mu = \sum_{f=u,d,s} \bar{q}_f\gamma_\mu\gamma_5 q_f \quad (7)$$

diverges at the quark level due to the one-loop triangle anomaly

$$\partial^\mu A_\mu = \frac{\alpha_s}{\pi}\cdot N_f \cdot tr\{F_{\mu\nu}\tilde{F}^{\mu\nu}\}, \quad (8)$$

where $\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\beta\gamma}F^{\beta\gamma}$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + [A_\mu A_\nu]$, $A_\mu = A^a_\mu\cdot\lambda^a$, α_s is the strong coupling constant, and N_f is the number of flavours. The anomaly induces a mixing between the gluon and the flavour singlet axial current of quarks. For this reason, the helicity carried by each flavour undergoes a renormalization

$$\Delta\tilde{q}_f(x,Q^2) = \Delta q_f(x,Q^2) - \frac{\alpha_s(Q^2)}{2\pi}\cdot\Delta G(x,Q^2). \quad (9)$$

It was suggested in [22] that the axial anomaly might play a key role and modify the naive quark model predictions; hence parton distributions will presumably become much more sensitive to the sign of the polarized gluon distribution. Consequently, the spin-dependent structure functions g_1^p and g_1^n would become more sensitive to ΔG, as well.

2.4 Integral Parton Contributions to the Proton Spin

A further input required to our analysis is the total contribution of each quark species to the proton spin. We utilize the results of a recent analysis [23] of the structure functions g_1^p and g_1^d from SMC and SLAC data incorporating 3^{rd} order pQCD corrections to the Bjorken sum rule. The relative quark contributions to the proton spin were determined as $\Delta\tilde{u} = 0.83\pm0.03, \Delta\tilde{d} = -0.43\pm0.03, \Delta\tilde{s} = -0.10\pm0.03$ at a renormalization scale $Q_0^2 = 10$ (GeV/c)^2. Using these values and the definition

$$\int_0^1 \Delta\tilde{q}_f(x,Q_0^2)dx = \Delta\tilde{f}, \quad f = u,d,s \quad (10)$$

the free parameters α_f, β_f in the parametrization of our spin-dependent parton distributions $\Delta u_V, \Delta d_V, \Delta\bar{u}, \Delta\bar{d}, \Delta s, \Delta G$ were determined in [9].

3 Results and Discussion

In fig. 1 (a,b) and 2 (a,b) the x-dependence of g_1^p and g_1^n is shown for different parametrizations of parton distributions constructed with $\Delta G > 0$ (a) and $\Delta G < 0$ (b). The dashed, solid and dotted lines correspond to the parameters α_f, β_f taken from Table 1-3 and 4-6 of Ref. [9], respectively.

From fig. 1 (a,b) is seen that all theoretical curves for the *proton* structure function g_1^p are in reasonable agreement with experimental data [1, 16, 19], i.e. there seems to be no apparent sensitivity to the sign of ΔG. In contrast, from fig. 2 (a,b), displaying experimental data and theoretical curves for the *neutron* structure function xg_1^n, one can deduce a certain dependence of the theoretical curves on the sign of ΔG in the range $0.1 < x < 0.3$. Hence there is some hope that xg_1^n exhibits a certain sensitivity to the sign of ΔG.

Fig. 3 (a,b) shows the x-dependence of the *proton* structure function $xg_1^p(x, Q^2)$ at different values of four-momentum transfer, $Q^2 = 1, 10, 100$ (GeV/c)^2. The Q^2 behaviour of xg_1^p appears qualitatively different for $\Delta G > 0$ and $\Delta G < 0$, respectively. In the first case the maximum of the curve is moved to lower x with increasing Q^2, in the second one the position of the maximum is not affected. If $\Delta G > 0$ the prediction *increases* with Q^2 for $x < 0.01$. If $\Delta G < 0$, the prediction *decreases* with Q^2 over the full x-range.

Fig. 4 (a,b) displays the x-dependence of the *neutron* structure function $xg_1^n(x, Q^2)$ in the same fashion, i.e. for $Q^2 = 1, 10$ (GeV/c)^2. If $\Delta G > 0$ the differences for different Q^2 appear mainly at very low x-values and, in addition, at moderate $x \simeq 0.3$. This sensitivity to the sign of ΔG is to weak for present experimental errors, however, it might be used later when more precise data on $g_1^n(x, Q^2)$ should become available. For $\Delta G < 0$ one observes a rather strong Q^2-dependence at lower x-values and a somewhat characteristic dip at higher x, its position being almost independent on Q^2.

To be closer to the presently available Q^2-values we show in fig. 5 the x-dependence of $xg_1^n(x, Q^2)$ at $Q^2 = 1, 3, 5, 10$ (GeV/c)^2 together with the presently available experimental data. (Due to the experimental errors the different ordinate is choosed in fig. 5(d) than in fig. 5(a,b,c).) The behaviour of xg_1^n on Q^2 is qualitatively and quantitatively different for the two scenarios $\Delta G > 0$ and $\Delta G < 0$, especially at low Q^2. Apparently, in the range $x < 0.1$ the experimental data on g_1^n at $Q^2 < 10$ (GeV/c)^2 should be able to discriminate between positive and negative sign of the polarized gluon distribution.

We apply a χ^2 criterion to quantitatively distinguish between the two scenarios by comparing our constructed parton distributions to the experimental data sets from SLAC and CERN [2, 3, 18]. The obtained results are summarized in Table 1. There the references for experimental data on g_1^n, the average Q^2 values, and the number of experimental points are shown in column 1, 2, and 3, respectively. The 'all' in col. 2 takes into account that each individual experimental point was measured at another average Q^2, i.e. here the χ^2 is calculated using in the theoretical calculation the correct average Q^2-value at each x-point. The corresponding kinematically accessible ranges are $1.1 \div 5.2$ (GeV/c)^2 for E142 and $1.3 \div 48.7$ (GeV/c)^2 for SMC. This method seems to us the closest possible description of the data by a theoretical calculation, hence we expect the χ^2 values obtained for the 'all' comparison to yield the best possible separation.

Experiment	$< Q^2 >$ $(GeV/c)^2$	data points	χ^2 / ndf $\Delta G > 0$	χ^2 / ndf $\Delta G < 0$
E142 [18]	2	8	1.20	2.05
E143 [2]	3	9	0.89	1.41
SMC [3]	10	12	1.28	1.63
HERMES [24]	3	8	0.86	1.20
E142 [18]	all	8	1.45	2.30
SMC [3]	all	12	1.35	2.41

Table 1. χ^2 comparison between theoretical predictions, calculated for the two scenarios $\Delta G > 0$ and $\Delta G < 0$, and experimental data on $g_1^n(x, Q^2)$.

From table 1 one can see that for every data set the χ^2 per degree of freedom is significantly better in the case $\Delta G > 0$ compared to the case $\Delta G < 0$. These results can be considered as clear quantitative evidence that the case $\Delta G > 0$ is the more likely scenario compared to the case $\Delta G < 0$.
We note that our result supports the conclusion on a positive sign of $\Delta G > 0$ obtained recently by a NLO QCD fit to g_1 proton and deuteron data [8].

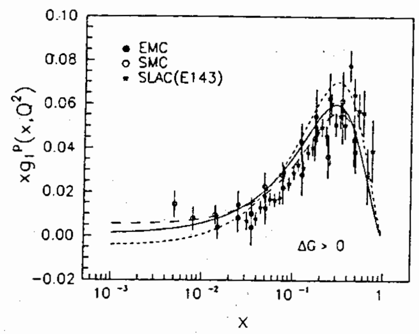
Finally we present in table 2 our results for the integral quark - $\Delta\Sigma$ - and gluon - Δg - contributions to the proton spin calculated with the low limit $x_{min} = 10^{-3}$. Whereas in the more likely scenario $\Delta G > 0$ the quark contribution $\Delta\Sigma$ appears to be almost stable with Q^2 it drops by almost a factor of 2 when increasing Q^2 from 3 to 10 (GeV/c)^2 in the less likely case $\Delta G < 0$. In both scenarios Δg rises by about 10% within the same Q^2 range.

Q_0^2 $(GeV/c)^2$	$\Delta\Sigma$ $\Delta G > 0$	$\Delta\Sigma$ $\Delta G < 0$	Δg $\Delta G > 0$	Δg $\Delta G < 0$
3	0.290	0.520	1.78	-3.01
5	0.293	0.420	1.86	-3.20
10	0.298	0.296	1.95	-3.41

Table 2. Integral quark - $\Delta\Sigma$ - and gluon - Δg - contributions to the proton spin, calculated from the constructed polarized parton distribution functions for the two scenarios $\Delta G > 0$ and $\Delta G < 0$.

4 Conclusions

The possibility to draw conclusions on a positive or negative sign of the polarized gluon distribution $\Delta G(x, Q^2)$ was studied using a phenomenological procedure to construct spin-dependent parton distributions. The method includes some constraints on the signs of valence and sea quark distributions, takes into account the axial gluon anomaly and utilizes results on integral contributions to the nucleon spin, $\Delta \bar{u}, \Delta \bar{d}, \Delta \bar{s}$. Investigating the x- and Q^2-dependencies of the structure functions g_1^p and g_1^n constructed by this method we introduce a χ^2 criterion to discriminate between the two scenarios obtained for $\Delta G > 0$ and $\Delta G < 0$, respectively. The neutron structure function turned out to be sufficiently sensitive to the sign of $\Delta G(x, Q^2)$, even at the present level of only moderate experimental errors. The results of our analysis strongly support the conclusion that the sign of $\Delta G(x, Q^2)$ is positive. New data on the neutron structure function g_1^n from the latest SLAC experiments and from HERMES at DESY will undoubtedly allow to draw a more definite conclusion on the sign of the polarized gluon distribution.



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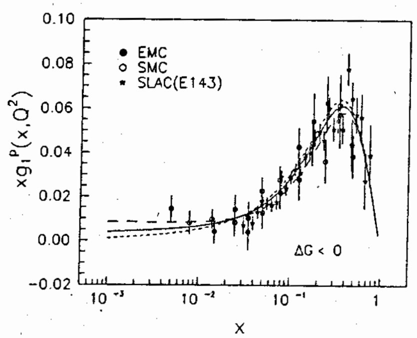
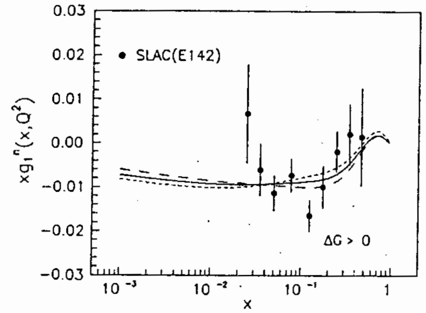


b)

Figure 1. Deep-inelastic proton structure function $xg_1^p(x,Q^2)$. Experimental data: $\star$ - [1], $\bullet$ - [16], $\circ$ - [19]. Theoretical curves: (a) - $\Delta G > 0$ and (b) - $\Delta G < 0$ at $Q^2 = 10\ (GeV/c)^2$. Parametrizations of parton distributions: - - - , ——— , — — are taken from Tables 1-3 and Tables 4-6 [9], respectively.



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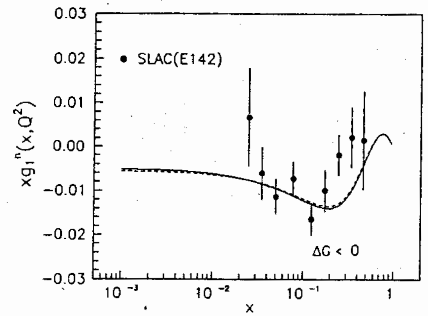
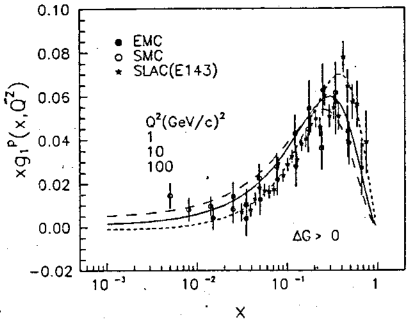


b)

Figure 2. Deep-inelastic neutron structure function $xg_1^n(x,Q^2)$. Experimental data: $\bullet$ - [18]. Theoretical curves: (a) - $\Delta G > 0$ and (b) - $\Delta G < 0$ at $Q^2 = 10\ (GeV/c)^2$. Parametrizations of parton distributions: - - - , ——— , — — are taken from Tables 1-3 and Tables 4-6 [9], respectively.



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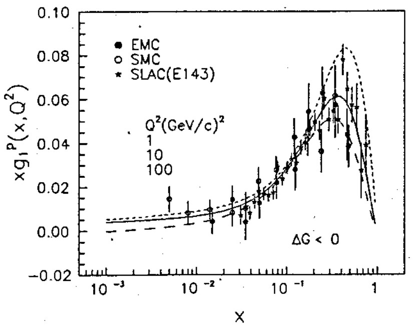
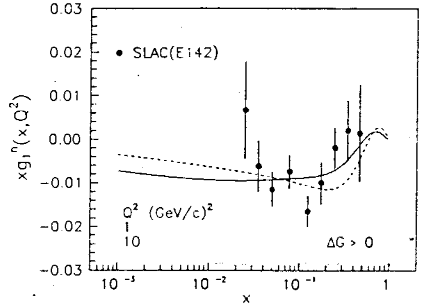


b)

Figure 3. Deep-inelastic proton structure function $xg_1^p(x, Q^2)$. Experimental data: $\star$ - [1], $\bullet$ - [16], o - [19]. Theoretical curves: (a) - $\Delta G > 0$, (b) - $\Delta G < 0$ and - - - - 1 $(GeV/c)^2$, ——— - 10 $(GeV/c)^2$, — — - 100 $(GeV/c)^2$. Parametrizations of parton distributions are taken from Tables 2 and 5 [9].



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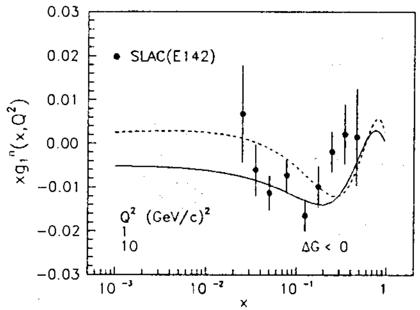

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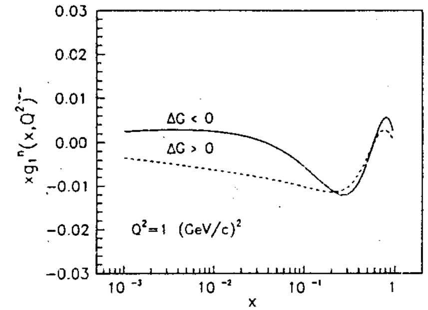
Figure 4. Deep-inelastic neutron structure function xg_1^n. Experimental data: $\bullet$ - [18]. Theoretical curves: (a) - $\Delta G > 0$, (b) - $\Delta G < 0$ and - - - - 1 $(GeV/c)^2$, ——— - 10 $(GeV/c)^2$. Parametrizations of parton distributions are taken from Tables 2 and 5 [9].



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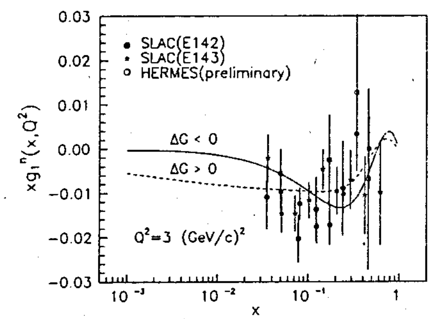
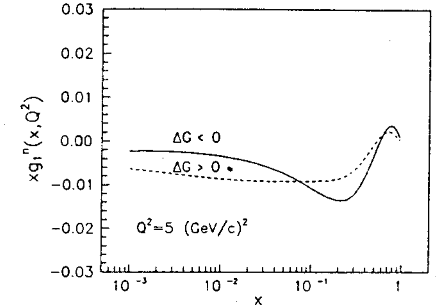


b)

Figure 5. Deep-inelastic neutron structure function $xg_1^n(x,Q^2)$. Experimental data: $\star$ - [2], $\triangle$ - [3], $\bullet$ - [18], $\circ$ - [24]. Theoretical curves: - - - - $\Delta G > 0$, ——— - $\Delta G < 0$ at $Q^2 = 1, 3, 5, 10\ (GeV/c)^2$. Parametrizations of parton distributions are taken from Tables 2 and 5 [9].



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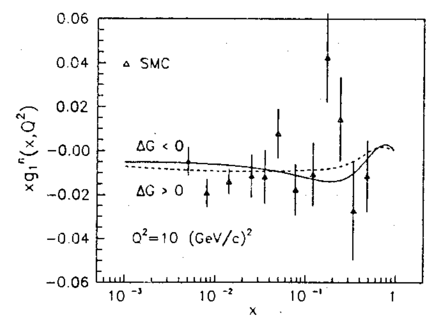

d)

Figure 5. Continued

Acknowledgements

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