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# Consistent Analysis of the Spin Content of the Nucleon

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## Abstract

The recent measurements of lepton nucleon scattering with polarised neutron and deuteron targets are analysed together with the previous polarised proton data in a mutually consistent way. The detailed $x$-dependence of the polarisation asymmetry in the valence region is shown to be in agreement with historical predictions based on quark models. The Bjorken sum rule is shown to be confirmed at the $1\sigma$ level and estimates of the spin content of the nucleon $\Delta q$ are extracted. While the average value of $\Delta q$ from the three experiments comes out to be $0.41 \pm 0.05$ (to be compared with the naive quark model theoretical expectation of 0.58) this experimental average value is more than one standard deviation from the value obtained from any individual experiment. This inconsistency can be overcome by allowing arbitrary higher twist contributions but the resulting precision is poor, $\Delta q = 0.38 \pm 0.48$.

# Introduction

The recent measurements of the polarised nucleon structure functions $g_1$ for the deuteron[1] and the neutron[2] have re-kindled the debate over the spin content of the nucleon which began with the measurement of $g_1$ for the proton[3] five years ago. The value of $I_p = \int g_1^p(x)dx$ extracted in ref[3] was consistent with a tiny fraction of the proton's spin being carried by the constituent quarks and this fuelled enormous speculation over our understanding of the nucleon in the quark model framework. Reviews of the various interpretations of this result and of the competing descriptions of the proton's spin structure can be found in ref [4].

In order to draw conclusions from the three experiments it is important to compare them consistently, in particular at the same $Q^2$ and with the same ancillary inputs (e.g. the unpolarised $F_1(x, Q^2)$ used in constructing the polarised structure function $g_1(x, Q^2)$ from the measured asymmetry $A_1(x)$). It is the purpose of the present paper to do this. A central plank in our analysis will be the asymmetry $A_1(x)$ and we begin with a comment on this measured quantity.

A significant feature of the data is that the $x$-dependences of the *polarisation asymmetry* in the valence region, $A_1(x > 0.2)$, confirm the quark model predictions[5][6] for proton, neutron (see fig.1) and deuteron systems. This suggests to us that there is an immediate message from these data:

**The polarisation of the *valence* quarks is canonical**

and this should be taken into account in any attempt to interpret the data. The $A(x)$ has tended to be ignored in the literature while most of the attention, and associated controversy, has arisen from the value of the *integrated structure function $g_1(x)$* and its interpretation. Much of our paper will address the implications of the new data for this question.

One obvious intention of a simultaneous analysis of $g_1^p$, $g_1^n$ and $g_1^d$ is to compare the experimental estimate of $I_{p-n}$ with Bjorken's fundamental sum rule[7]

$$I_{p-n}(Q^2) \equiv \int_0^1 \left( g_1^p(x, Q^2) - g_1^n(x, Q^2) \right) dx = \frac{1}{6} \frac{g_A}{g_V} \left[ 1 - \left( \frac{\alpha_s}{\pi} \right) - \frac{43}{12} \left( \frac{\alpha_s}{\pi} \right)^2 \right] \quad (1)$$

where we assume $n_f = 3$. Since the three experiments carry out measurements at different values of $Q^2$ one must be careful to combine the $p, n, d$ results at a common $Q^2$ to test the Bjorken sum rule. For this reason and for general requirements of consistency we shall take only the measurements of the *asymmetry* from refs[1, 2, 3] and use the latest sets of unpolarised structure functions and parton distributions to construct the polarised structure functions through

$$g_1(x) = A_1(x)F_1(x) = \frac{A_1(x)F_2(x)}{2x(1 + R(x))} \quad (2)$$

1

We find that $g_1^p$ (and $I_p$) of ref[3] is increased as a result of the new information on $F_2(x)$ from ref[8] at low $x$.

Also, in extracting 'experimental' estimates of the integrals $I_{p,n,d}$ we are guided by theoretical estimates of the asymmetry $A_1$ at *large* $x$ to cover the unmeasured region ($x > 0.6$). Even where the asymmetry is measured for $x > 0.3$ the experimental uncertainty tends to be large and can dominate the error on the integral (particularly SMC $d$ data), so we prefer instead to use the valence quark model (VQM) estimates of $A_1$ in this region also.

Comparison of the $I_{p,n,d}$ with the Ellis-Jaffe[9] predictions and the extraction of the spin content $\Delta q$ of the nucleon require knowledge of the F/D parameter and careful treatment of QCD corrections. We re-evaluate F/D in the light of recent $\beta$-decay measurements. We include the QCD corrections to the non-singlet and singlet contributions to the integrals. Indeed in the non-singlet case the corrections are known to second order at least[10] and significantly reduce the magnitude predicted for the Bjorken sum rule at low $Q^2$.

We find that analysing the data in this manner is consistent with the Bjorken sum rule at the $1\sigma$ level. We find $\Delta q = 0.41 \pm 0.05$ but the values from each of $p$, $n$ and $d$ lie outside the uncertainty of this mean value. Allowing for higher-twist contributions of arbitrary strength to force a common value of $\Delta q$ from $p, n$ and $d$ leads to $\Delta q = 0.38 \pm 0.48$. The errors on the higher twist terms themselves are thus large and, not surprisingly, are consistent with the rather precise theoretical estimates of ref[11] used in the recent analysis of Ellis and Karliner[12] which yields $\Delta q = 0.22 \pm 0.10$.

# Extraction of $g_1^{p,n,d}$ and $I_{p,n,d}$ from data

The EMC proton experiment is at $< Q^2 > \sim 11$ GeV$^2$, the SMC deuteron experiment is at $< Q^2 > \sim 5$ GeV$^2$ while the SLAC E142 experiment is at $< Q^2 > \sim 2$ GeV$^2$. To evaluate the structure functions at a common $Q^2$ value of 5 GeV$^2$ we take the measured values of the asymmetries $A_1^{p,n,d}(x)$ for each experiment and assume these values hold at $Q^2 = 5$ GeV$^2$. (There is excellent evidence for the $Q^2$ independence of $A_1^p(x)$ from ref [3] over the range 0.5 - 50 GeV$^2$; within the relatively large errors of ref[1] there is no evidence for any $Q^2$ dependence of $A_1^d(x)$. Furthermore, within the precision of the SLAC E142 experiment $A_1^n(x)$ appears to also to be independent of $Q^2$[13]). To construct the $g_1^i(x, Q^2)$ at $Q^2 = 5$ GeV$^2$ we take parton distributions to compute $F_1^{p,n}(x, Q^2)$ which are consistent with recent DIS data, in particular the $F_2$ data of NMC [8] at small $x$. We take the $D_0'$ or $D_-'$ distributions of MRS [14], the latter even providing an excellent description of the new data from HERA[15]. The reliable estimate of the gluon distribution in these fits provides, in turn, an estimate for $R_{QCD}$ to insert in eqn(2). We have checked that these results remain true when

the distributions of ref[16] are used instead.

The use of up-to-date unpolarised structure functions changes the values of $g_1^p(x)$ based on the EMC measurements at $Q^2 \sim 11$ GeV$^2$ by a significant amount; it is essentially the new information from NMC[8] measurements which increases the values of $g_1^p(x)$ and hence $I_p$ and $\Delta q$. Computing the $g_1^{p,n,d}(x)$ at the same $Q^2$ value now allows us to take combinations of pairs. In fig.2 we compare the values of $xg_1^d(x)$ computed from the $A_1^d$ of SMC with the combination $\frac{1}{2}(xg_1^p(x) + xg_1^n(x))$ computed from the EMC and SLAC asymmetry measurements. Point-by-point we see that the two estimates are consistent with each other.

In order to compute the integrals $I_{p,n,d}$ at $Q^2 = 5$ GeV we must extrapolate at small $x$ and large $x$. The small $x$ estimate of the integral is obtained by taking the smallest $x$ data point and assuming the behaviour of $xg_1 \sim x^\alpha$. Taking $\alpha = 0$ (as expected from Regge behaviour) gives the central value of this extrapolation and the error on this is the value obtained if $\alpha = 0.5$. Given that the HERA data on $F_2(x)$ are *larger* than naive Regge expectation, one may need to reevaluate the $g_1(x \to 0)$ extrapolation: our error estimate allows for some room in this direction. It is crucial that future experiments go to as small $x$ as possible in order to help settle this question. Fig.2 indicates that the estimate for the integral $\int_0^{0.03} g_1^d(x)dx$ from the $\frac{1}{2}(p + n)$ combination is rather different from the direct $d$ data.

At large $x$ we have some theoretical guidance for the asymmetries $A_1^{p,n}(x)$ from valence quark models[5]. Indeed, independent of the questions about the values of the $I_i$, the localised $x$-dependence in the valence region provides rather dramatic confirmation of predictions made far in advance of data on $n, d$ even $p$. We regard this as an important clue in interpreting the polarisation data and therefore draw attention to, and make a brief comment on, this aspect of the data which has tended to receive less attention than the integral.

As $x \to 1$ both $A_1^p, A_1^n$ were predicted to reach unity[5][17][18] but their values around $x = 0.5$ are expected to be quite different[5][6]. The expectations from the VQM are consistent with the measured values at $x = 0.35, 0.45$. We therefore use the VQM estimates of $A_1^{p,n}$ (with estimated uncertainties) to compute the large $x$ integral (i.e. $x > 0.6$). In addition we notice that the final errors in $I_{p,n,d}$ tend to be dominated by the last two values of the $g_1$ at $x = 0.35, 0.45$ where the cross-sections are small. With some caution, we choose to take the VQM values with their smaller uncertainties at these two $x$-values. Fig.2 also shows these values and we see that they are completely in line with the relatively precise values obtained from the $\frac{1}{2}(p + n)$ combination.

At $Q^2 = 5$ we compute the integrals and as a result of the above procedures obtain the following values:-

3

$$
\begin{aligned}
I_p(Q^2 = 5) &= 0.135 \pm 0.011 \\
I_n(Q^2 = 5) &= -0.028 \pm 0.006 \\
I_d(Q^2 = 5) &= 0.041 \pm 0.016
\end{aligned}
\tag{3}
$$

Note the value of $I_p$ is larger than the EMC quoted value (due to new NMC measurements of $F_2$) and note the larger central value of $I_d$ compared to that quoted by SMC - due to our model estimates at large $x$ (but $I_d = 0.041$ is within the quoted SMC uncertainty of course). From these values we can estimate in three ways the value of the Bjorken sum rule (where $d = (p + n)/2$) at $Q^2 = 5 GeV^2$:-

$$
\begin{aligned}
I_{p-n} &= 0.163 \pm 0.013 \\
I_{2(d-n)} &= 0.139 \pm 0.035 \\
I_{2(p-d)} &= 0.187 \pm 0.040
\end{aligned}
\tag{4}
$$

# Bjorken Sum Rule and Spin Content of the Nucleon

We can write for the first moments:-

$$
\begin{aligned}
I_p &= I_3 + I_8 + I_0 \\
I_n &= -I_3 + I_8 + I_0 \\
I_d &= I_8 + I_0
\end{aligned}
\tag{5}
$$

where

$$
\begin{aligned}
I_3 &= \frac{1}{12} a_3 \left(1 - \frac{\alpha_s}{\pi} - 3.58 \left(\frac{\alpha_s}{\pi}\right)^2\right) \\
I_8 &= \frac{1}{36} a_8 \left(1 - \frac{\alpha_s}{\pi} - 3.58 \left(\frac{\alpha_s}{\pi}\right)^2\right) \\
I_0 &= \frac{1}{9} a_0 \left(1 - \frac{\alpha_s}{3\pi}\right)
\end{aligned}
\tag{6}
$$

where the next-to-leading order QCD corrections to the non-singlet quantities have been evaluated in ref[10]. Note that the QCD corrections to the singlet are smaller. [1] In eqn(6) $a_3$ and $a_8$ are related to the F/D values while $a_0$ is the spin fraction carried by quarks, i.e.

$$
\begin{aligned}
a_3 &\equiv F + D \equiv \Delta u - \Delta d \\
a_8 &\equiv 3F - D \equiv \Delta u + \Delta d - 2\Delta s \\
a_0 &\equiv \Delta q \equiv \Delta u + \Delta d + \Delta s
\end{aligned}
\tag{7}
$$

---

[1]This is due to the non-vanishing of the singlet anomalous dimension $\gamma_{qq}^{(1),S,1}$[19]. The $O(\alpha_s)$ correction to the singlet coefficient function has recently been carried out[20].

4

Thus we need to know F, D precisely to extract a reliable estimate for $\Delta q$.

We have performed a fit of the current values of the $\beta-$decay constants for $np$, $\Lambda p$, $\Xi\Lambda$ and $\Sigma n$[21] and the best fit, with $\chi^2 = 1.55$ for one degree of freedom (F/D with F+D constrained to equal 1.257) is

$$\left.\begin{array}{rcl} F & = & 0.459 \pm 0.008 \\ D & = & 0.798 \mp 0.008 \end{array}\right\} F/D = 0.575 \pm 0.016 \qquad (8)$$

This is $1\sigma$ larger than the value used in a previous analysis of ours [22] principally due to improved $\Lambda p$ and $\Sigma n$ data. We shall use these values in what follows; however there are two caveats. First there is a systematic error, not included, whch arises from the phase space or form factor corrections in the $\Delta S = 1$ examples[23]. The second is potentially more serious.

The quoted figures assume that in the hadronic axial current

$$A_\mu = g_A \gamma_\mu \gamma_5 - g_2 \frac{i\sigma_{\mu\nu} q^\nu \gamma_5}{m_i + m_j} \qquad (9)$$

one has $g_2 = 0$. While this is assured in the limit where $m_i = m_j$ (such as $n \to p$) it is not necessarily so for $\Delta S = 1$. Indeed, in quark models one expects that $g_2 = 0(\frac{m_i - m_j}{m_{ij}})$ with $m_{ij} \equiv \frac{1}{2}(m_i + m_j)$[24].

Hsueh et al.[25] made a fit allowing for $g_2 \neq 0$ and found a significant change in their inferred value for $g_A$. A best fit incorporating this value raises a tantalising possibility that the $(g_A/g_V)$ throughout the octet are given by the naive quark model, all values being renormalised by 25% (such that the net spin is 0.75 rather than 1). Such an eventuality would correspond to the realisation of the effective quark model result

$$F = 1/2, \ D = 3/4 \quad ; \quad F/D = 2/3 \qquad (10)$$

This is discussed elsewhere[26]. These additional theoretical uncertainties merit further study: for the purpose of comparing most directly with the literature we shall adopt the $g_2 = 0$ best fit, eq(8).

Since the error on F+D is so small, the uncertainty on the Bjorken sum rule prediction comes only from the $\alpha_s$ uncertainty:we take $\alpha_s = 0.28 \pm 0.02$ at $Q^2 = 5$ GeV$^2$ which gives $I_{p-n} = 0.183 \to 0.187$. We note that actually the $0(\alpha_s^3)$ correction estimate in ref[10] is again, like the coeffs of $\alpha_s$ and $\alpha_s^2$, negative. In fig.3(a) we compare our estimates from eqn(4) with this value and we see no serious discrepancy. Remember that our procedure at large $x$ produces uncertainties which are smaller than the true experimental errors - using the latter would further reduce any possible discrepancy in fig.3(a).

With the above values of F/D and $\alpha_s$, the Ellis-Jaffe[9] predictions (i.e. $\Delta s = 0$) of the integrals $I_{p,n,d}$ are

$$I_p = 0.172 \pm 0.009$$
$$I_n = -0.018 \pm 0.009$$
$$I_d = 0.077 \pm 0.009 \qquad (11)$$

and these are compared with the values from eqn(3) in fig.3(b). Despite the increased estimate of $I_p$ from the EMC data we see that only $I_n$ is consistent with the assumption of $\Delta s = 0$. Extracting the values of $\Delta q$ from eqns (3,5,6,7) gives

$$I_p \Rightarrow \Delta q = 0.21 \pm 0.11 \qquad (\Delta s = -0.12 \pm 0.04)$$
$$I_n \Rightarrow \Delta q = 0.49 \pm 0.06 \qquad (\Delta s = -0.03 \pm 0.02)$$
$$I_d \Rightarrow \Delta q = 0.24 \pm 0.15 \qquad (\Delta s = -0.11 \pm 0.05) \qquad (12)$$

to be compared with the theoretical expectation $\Delta q = 3F - D = 0.58$; these are shown in fig.3(c). The mean value of the spin content from the three determinations is

$$< I_{p,n,d} > \quad \Rightarrow \quad < \Delta q > = 0.41 \pm 0.05 \qquad (13)$$

the value being driven largely by the relatively small errors on the neutron estimate.

Although these determinations agree at $1\sigma - 2\sigma$, it is nonetheless somewhat unsatisfactory that the three determinations fail to give a mutually consistent value of the nucleon spin content. We note that the $p, d$, which are at moderately high values of $Q^2$ agree while it is the neutron data at low $Q^2$ that appear to be out of line. This calls into question the assumption made in the determination of the $g_1$ from the data on $A_1$ and suggests that there may indeed be significant $Q^2$ dependence of $A_1^n(x)$ between $Q^2 = 2$ and 5 GeV$^2$ which we have neglected. We know that leading twist alone is insufficient to explain the unpolarised structure functions for $Q^2$ below $\sim 4$ GeV$^2$ and therefore it seems sensible to allow for some arbitrary higher twist contributions to the first moments of $g_1$. Hence we write

$$I_p = I_3 + I_8 + I_0 + a_p/Q^2$$
$$I_n = -I_3 + I_8 + I_0 + a_n/Q^2$$
$$I_d = I_8 + I_0 + (a_p + a_n)/2Q^2 \qquad (14)$$

We now evaluate each integral at the relevant $Q^2$, i.e. $I_p$ at $Q^2 = 10.7$ GeV$^2$, $I_d$ at $Q^2 = 4.6$ GeV$^2$ and $I_n$ at $Q^2 = 2$ GeV$^2$. [2] We still use the MRS[14] distributions for $F_1(x, Q^2)$ for determining $g_1^{p,d}$ but, as these are not valid below 5 GeV$^2$, for the

---

[2] While we are now stressing possible $Q^2$ dependence we should be concerned that even within the EMC and SMC experiments there is a different $Q^2$ range for each $x$-value. If this is true also for the SLAC experiment then our higher twist analysis could be affected.

determination of $g_1^n(x, Q^2 = 2)$ we use both the NMC [8] and SLAC[27] data on $F_2$ and $R$. As a result, we now get

$$
\begin{aligned}
I_p(Q^2 = 10.7) &= \phantom{-}0.134 \pm 0.012 \\
I_n(Q^2 = \phantom{1}2.0) &= -0.023 \pm 0.005 \\
I_d(Q^2 = \phantom{1}4.6) &= \phantom{-}0.041 \pm 0.016
\end{aligned}
\tag{15}
$$

Taking $\alpha_s = 0.26$ at $Q^2 = 10.7$, $\alpha_s = 0.36$ at $Q^2 = 2$ GeV$^2$ we can extract the values of $a_p$ and $a_n$ from eqn (14) by insisting on a *common* value of $\Delta q$ from all three equations, using the same values of F and D as before.

As a result we obtain

$$
\Delta q = 0.38 \pm 0.48
\tag{16}
$$

with

$$
\begin{aligned}
a_p &= -0.161 \pm 0.530 \\
a_n &= \phantom{-}0.030 \pm 0.104
\end{aligned}
\tag{17}
$$

We see that the errors on $I_{p,n,d}$ are such that the higher twist contributions and $\Delta q$ cannot be pinned down with any precision. The above values in eqn(17) easily encompass the QCD sum rule estimates of Balitsky et al[11] used in the analysis of Ellis and Karliner[12],

$$
\begin{aligned}
a_p &= -0.005 \pm 0.040 \\
a_n &= \phantom{-}0.039 \pm 0.040
\end{aligned}
\tag{18}
$$

The analysis of ref[12] concluded that $\Delta q = 0.22 \pm 0.10$ and we can see that our analysis indicates the sensitivity of this result to the magnitude of the higher twist terms. Also we see that the higher twist contribution can make a substantial reduction to the magnitude of the Bjorken sum rule. We note also that $O(1/Q^2)$ terms occur naturally when the Bjorken and Drell-Hearn-Gerasimov[28] sum rules are derived in explicit quark models[29]. Indeed their magnitudes are consistent with the general bounds of eqn(17).

An interesting consequence of the values of $a_p$ and $a_n$ in eqn(18) is that it is primarily the neutron which would be expected to be most affected at low $Q^2$ leading to possible dramatic effects for $g_1^n(x, Q^2)$. With the above value for $a_n$, $I_n$ would be expected to change by around 50% between $Q^2$ of 2 and 5 GeV$^2$ and we can speculate how $g_1^n(x, Q^2)$ itself would alter to bring this dramatic increase in the size of $I_n$. At present the only guide we have is a comparison of $[xg_1^d(x, Q^2 = 5) - xg_1^p(x, Q^2 = 5)]$ extracted from SMC and EMC. There is a hint from this comparison that the increase would occur at very low $x$, especially if we keep faith with the VQM prediction for $x > 0.3$. However since the SLAC data stop at $x = 0.03$ it is also possible that $g_1^n$

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may be much larger in magnitude for $x < 0.03$, even at $Q^2 = 2$ GeV$^2$, causing $I_n$ at $Q^2 = 2$ GeV$^2$ to be larger than supposed. In that case any higher twist analysis would have to be severely modified.

Our analysis shows the importance of continued experimentation in this area. The situation should become clearer when SMC (who reach the smallest $x$ values of all three experiments) have accumulated their full data sample and when SLAC are able to continue their experiment for a polarised proton target. We have stressed the importance of comparing $g_1^{p,n,d}(x, Q^2)$ and their integrals $I_{p,n,d}$ at the same value of $Q^2$ in order to pin down the spin content of the nucleon. The exercise of including higher twists in the analysis of present data indicates the extreme sensitivity of the spin content of the nucleon to their magnitude.

In conclusion we reiterate that the successful quark model predictions of the $A(x > 0.1)$[5, 6] imply that valence quarks are polarised canonically and that there is no need to rewrite the textbooks in light of these data. Immediate questions to be answered include whether $A^n(x \to 1) > 0$ [5][18]; with this exception the behaviour of $A(x)$ in the valence region seems established and most effort is needed in the $x \to 0$ region. In addition to the questions advertised above, we urge test of whether $g_1^d(x \to 0) < 0$ as this may enable a "direct" measure of $\Delta q$[22, 26]. Finally, if the valence quarks are indeed polarised canonically then it becomes important to make direct measure of the sea polarisarion. Ref.[30] has argued that semi-inclusive production of fast $K^-$ in polarised leptoproduction may enable the polarisation of $s$ and/or $\bar{u}$ to be probed.

# Acknowledgment

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# Figure Captions

[1] Polarisation asymmetries $A_1^p(x, Q^2)$ and $A_1^n(x, Q^2)$ from the EMC[3] and SLAC E142[2] experiments compared with the predictions of valence quark model[5]. The curves[5] correspond to $A_1^p = \frac{19-16R}{15}\xi$, $A_1^n = \frac{2-3R}{5R}\xi$, with $R = \frac{F_1^n}{F_1^p}$ and $\xi = 1$ (solid), $\xi = 0.75$ (dashed). See ref[26] for further details.

[2] $xg_1^d(x, Q^2 = 5)$ extracted from the SMC data on $A_1^d(x)$ and $g_1^{\frac{1}{2}(p+n)}(x, Q^2 = 5)$ from the corresponding data on $A_1^{p,n}(x)$ from EMC and SLACE142. Also included are the values at large $x$ expected from the valence quark model.

[3(a)] Values of Bjorken sum rule $I_{p-n}$ extracted from the values of $I_{p,n,d}$ at $Q^2 = 5$ GeV$^2$. The shaded region is the theoretical prediction.

[3(b)] $I_{p,n,d}$ extracted at $Q^2 = 5$ GeV$^2$ compared to the expectation of the Ellis-Jaffe sum rules, $\Delta s = 0$.

[3(c)] Values of $\Delta s$ and $\Delta q = \Delta u + \Delta d + \Delta s$ extracted from the estimates of $I_{p,n,d}$ at at $Q^2 = 5$ GeV$^2$.
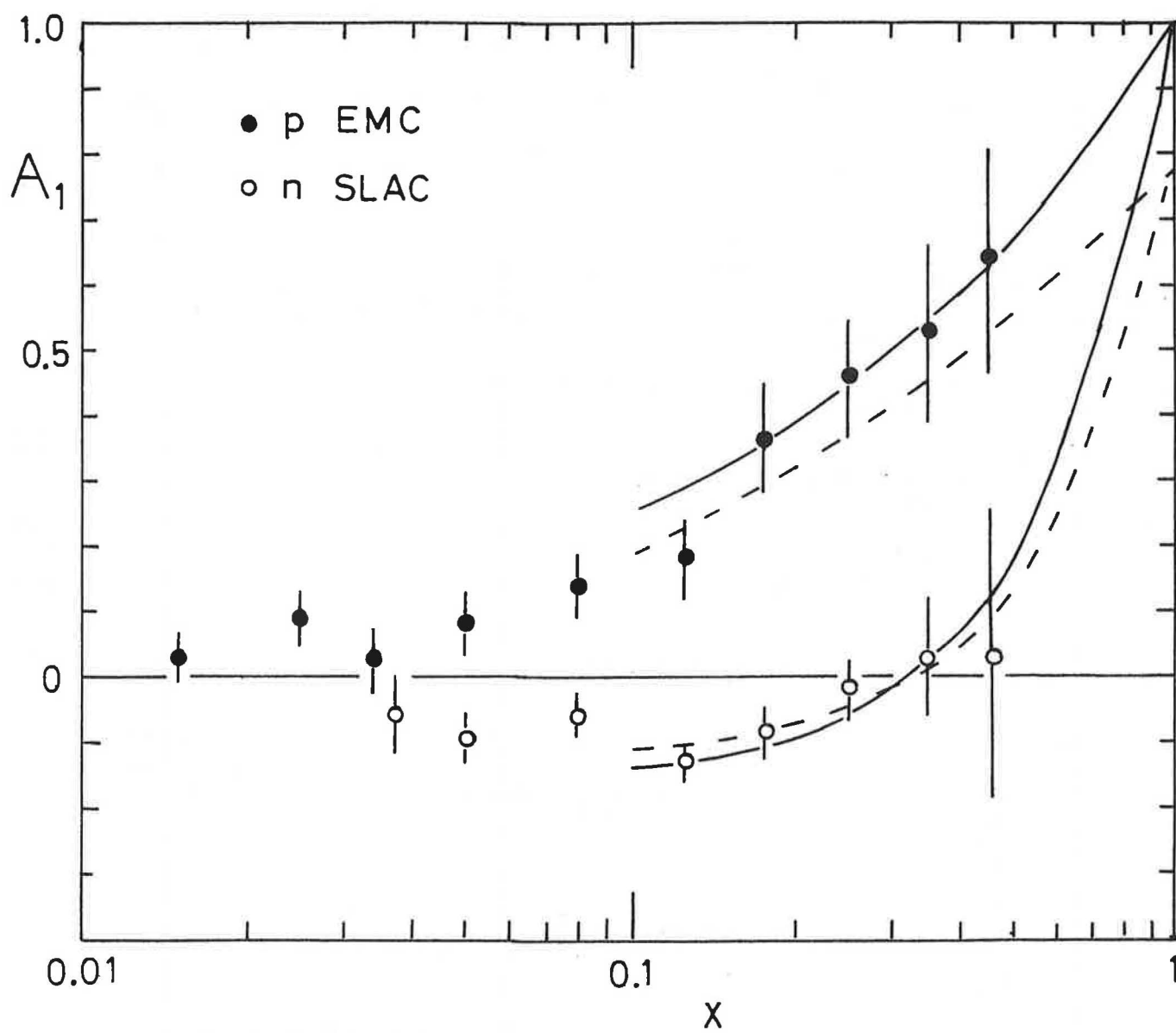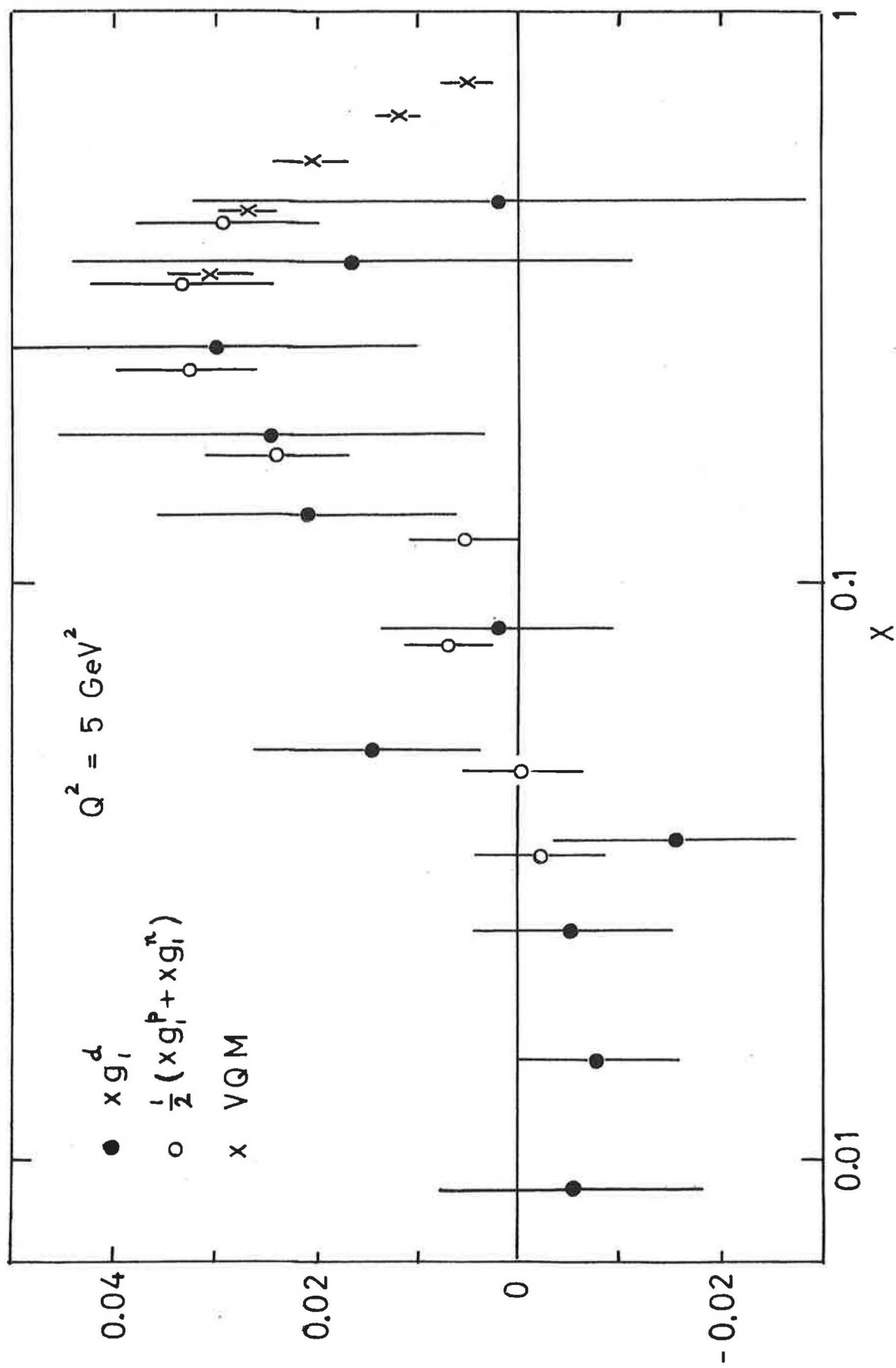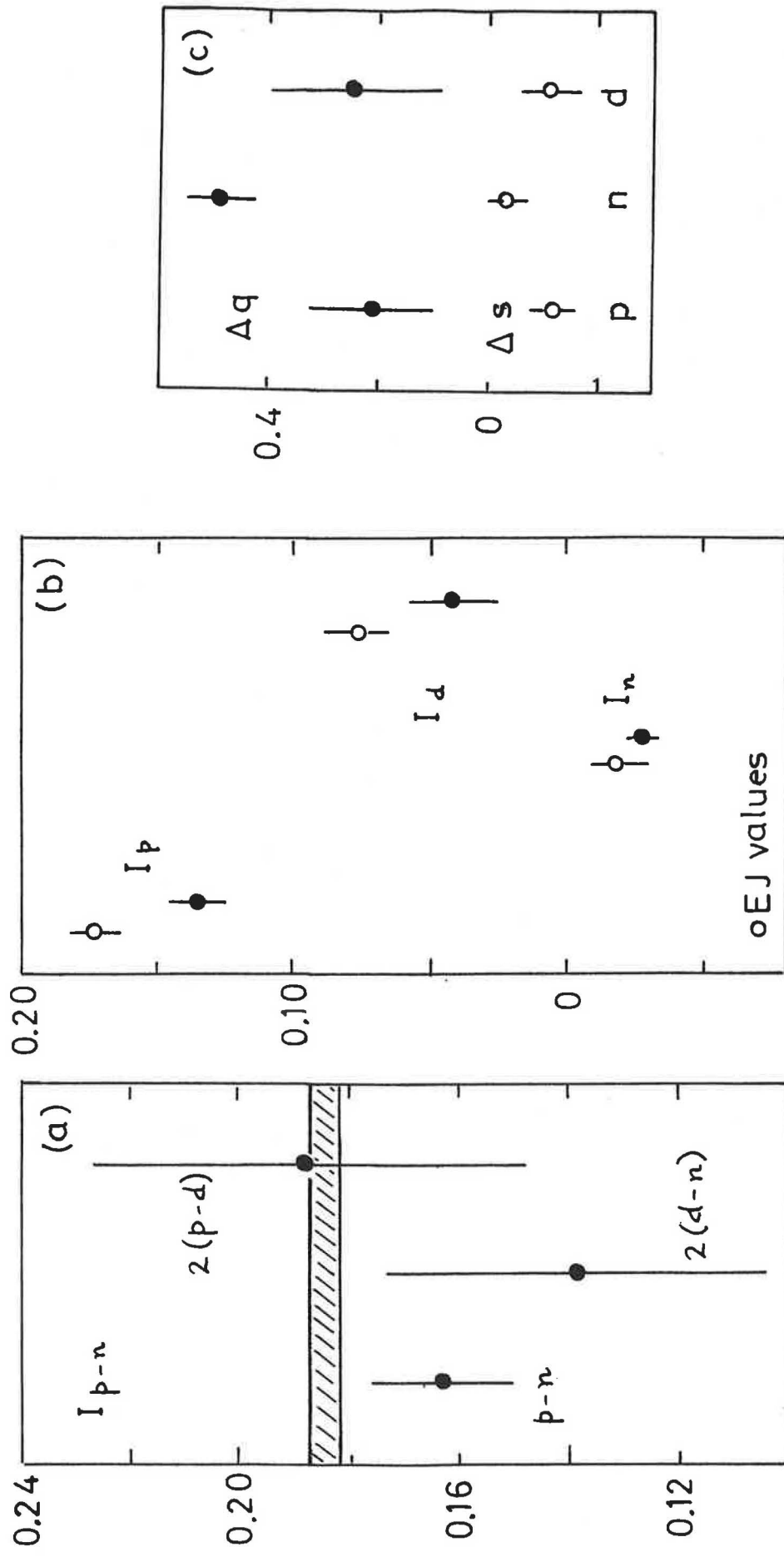
**Fig. 1**

Fig. 2

Fig. 3