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Target Fragmentation at Polarized HERA: A Test of Universal Topological Charge Screening in QCD [1]

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Abstract

Topological charge screening has been proposed as the mechanism responsible for the anomalous suppression in the first moment of the polarized proton structure function – the 'proton spin' effect. An immediate consequence is that this suppression should be target-independent, since the screening is a fundamental property of the QCD vacuum. Here, we study the possibility of testing the target-independent suppression in semi-inclusive target fragmentation processes at polarized HERA.

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1 Polarized Structure Functions and Universal Screening of Topological Charge

The last decade has seen an important advance in our understanding of polarized nucleon structure functions as a result of inclusive DIS data obtained by several experimental collaborations. It is now confirmed at the 10% level that the Bjorken sum rule for g_1^p and g_1^n is correct. On the other hand, the Ellis-Jaffe sum rule is violated or, equivalently, the flavour singlet axial charge a^0 of the proton or neutron is significantly less than its OZI value.

In the QCD parton model, the breaking of the Ellis-Jaffe sum rule is understood as due to a positive polarized gluon distribution and/or a negative polarized strange quark distribution in a^0. The interpretation of the axial charges in terms of polarized parton distributions depends on the factorization scheme. In the AB scheme,

$$a^3 = \Delta u - \Delta d\,, \qquad a^8 = \Delta u + \Delta d - 2\Delta s\,, \qquad a^0(Q^2) = \Delta\Sigma - n_f \frac{\alpha_s(Q^2)}{2\pi}\Delta g(Q^2)\,. \tag{1}$$

All the scale dependence of $a^0(Q^2)$ is assigned to the polarized gluon, leaving the singlet quark distribution $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ scale-invariant. The Ellis-Jaffe sum rule arises from the approximation $a^0(Q^2) = a^8$, equivalent to the OZI rule. (For a recent theoretical review of the 'proton spin' effect, see e.g. ref. [1].)

An interesting conjecture is that the observed suppression in $a^0(Q^2)$ is due overwhelmingly to the gluon distribution $\Delta g(Q^2)$. If so, the strange quark distribution in the proton is almost zero, $\Delta s \simeq 0$, and $\Delta\Sigma \simeq a^8$ (preserving the spirit of the original Ellis-Jaffe proposal). This is a theoretically appealing idea because it is the axial $U(1)_A$ anomaly (which is due to the gluons and is responsible for OZI violations in other channels) that is responsible for the scale dependence of $a^0(Q^2)$ and $\Delta g(Q^2)$, whereas $\Delta\Sigma$ is scale-invariant.

However, from the present inclusive proton and neutron data, it is not possible to isolate the quark distributions for each flavour, while information on the polarized gluon distribution comes only from analysing the scale dependence of $g_1^N(Q^2)$. It is therefore not yet possible to determine accurately the contributions of Δs and Δg to the violation of the Ellis-Jaffe sum rule.

To make further progress in understanding the polarized structure of the nucleon, it is absolutely necessary to study less inclusive processes. The usual semi-inclusive asymmetries will be essential for determining the quark flavour decomposition, whereas open charm, jet and charged hadron production (for both DIS and real photons) will give information on the polarized gluon distribution. All of these are *current fragmentation* processes and most can be studied at polarized HERA. However, in contrast to fixed-target experiments such as COMPASS, polarized HERA is unique in being able to study the *target fragmentation* region. We now explain the importance of target fragmentation data in revealing the ultimate origin of the OZI breaking responsible for the violation of the Ellis-Jaffe sum rule.

It has been proposed that the anomalous suppression of the first moment of the polarized structure function is not a special property of the proton and neutron or of their parton distributions, but is a *target-independent* phenomenon, which would hold for any hadron [2]. It is due to a universal screening of topological charge inherent in QCD itself.

To understand this screening mechanism, note first that using the axial $U(1)_A$ anomaly $\partial^\mu A^0_\mu = 2n_f \frac{\alpha_s}{8\pi} G\tilde{G}$, the flavour singlet axial charge is just the forward matrix element of the gluon topological charge density $\frac{\alpha_s}{8\pi} G\tilde{G}$, i.e.

$$a^0(Q^2)\,\overline{N}\gamma_5 N = \frac{1}{2M} 2n_f \langle N|\frac{\alpha_s}{8\pi} G\tilde{G}|N\rangle\,. \tag{2}$$

The matrix element is then decomposed into a composite operator propagator and a vertex, which is chosen to be scale-independent. It is conjectured in refs. [2, 3] that all the OZI violation in $a^0(Q^2)$ resides in the scale-dependent propagator, while the vertex, which contains all the information on the target, is well approximated by the OZI rule. This implies

$$a^0(Q^2) = s(Q^2)\, a^0_{OZI}\,, \tag{3}$$

where, for the proton or neutron, $a^0_{OZI} = a^8$ and $s(Q^2)$ is a universal suppression factor. Using chiral Ward identities, $s(Q^2)$ can be shown to be determined by the QCD topological susceptibility $\chi(k^2)$, which measures the response of the QCD vacuum to topological charge. Precisely,

$$s(Q^2) = \frac{\sqrt{2n_f}}{f_\pi}\sqrt{\chi'(0)}\,, \tag{4}$$

where $\chi'(k^2) = d\chi(k^2)/dk^2$ and

$$\chi(k^2) = \int dx\, e^{ik.x} i\langle 0|T\ \frac{\alpha_s}{8\pi}G\tilde{G}(x)\ \frac{\alpha_s}{8\pi}G\tilde{G}(0)|0\rangle\,. \tag{5}$$

The existing inclusive proton and neutron data suggest that s is in the range 0.3 to 0.7 at $Q^2 = 10$ GeV^2, while a QCD spectral sum rule calculation [2] in the chiral limit gives $s \simeq 0.6$.

The physical picture is therefore that the QCD vacuum screens the topological charge in the matrix element for $a^0(Q^2)$, and so the singlet axial charge of any hadron is OZI-suppressed by a universal factor $s(Q^2)$. The mechanism is analogous to the screening of electric charge in QED. There, because of the Ward identity, the screening is given entirely by the ('target-independent') dressing of the photon propagator by the vacuum polarization diagrams (cf. eqs. (4),(5)), leading to the relation $e_R = e_0\sqrt{Z_3}$ (with $Z_3 < 1$) between the renormalized and bare charges, in close analogy with eq. (3) above.

To test this picture directly we would need to perform DIS experiments on targets other than the proton and neutron. The proposal of ref. [3] is that this can in effect be done by studying semi-inclusive processes in which a single hadron carrying a large target energy fraction is detected in the target fragmentation region.

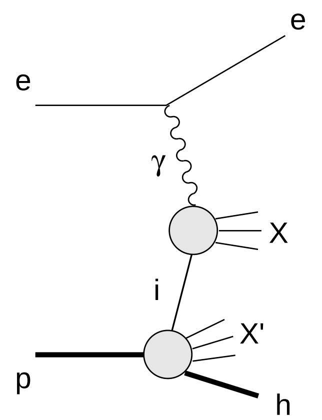

Fig.1 Semi-inclusive DIS: target fragmentation region.

Semi-inclusive DIS in the target fragmentation region, as shown in Fig. 1, is best described using (extended) fracture functions [4, 5] $M_i^{h/N}(x, z, t, Q^2)$, which represent the joint probability distribution for producing a parton i with momentum fraction x and a detected hadron h carrying an energy fraction $z = p_2' \cdot q / p_2 \cdot q$ from a nucleon N; t is the invariant momentum transfer. The polarized cross section is given at LO [6] (neglecting NLO current fragmentation effects) by

$$\frac{d\Delta\sigma^{target}}{dx dQ^2 dz dt} = \frac{4\pi\alpha^2 y(2-y)}{Q^4} \Delta M_1^{h/N}(x,z,t,Q^2)\,, \tag{6}$$

with the fracture equivalent of the inclusive g_1

$$\Delta M_1^{h/N}(x,z,t,Q^2) = \sum_i \frac{\hat{e}_i^2}{2} \Delta M_i^{h/N}(x,z,t,Q^2)\,. \tag{7}$$

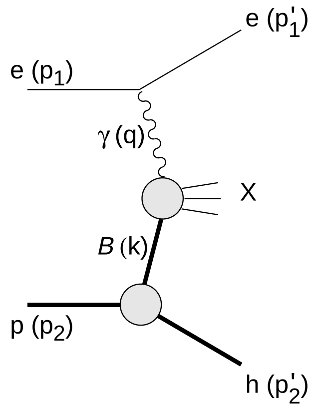

Fig.2 Single Reggeon exchange model of $ep \to ehX$.

For large z, i.e. for the hadron carrying a large energy fraction, the process may be simply modelled by a single Reggeon exchange diagram (Fig. 2), which corresponds to the approximation

$$\Delta M_1^{h/N}(x,z,t,Q^2) \underset{z\to 1}{\simeq} F(t)(1-z)^{-2\alpha_{\mathcal{B}}(t)} g_1^{\mathcal{B}}\left(\frac{x}{1-z}, t, Q^2\right)\,, \tag{8}$$

where $g_1^{\mathcal{B}}$ is the structure function for the exchanged Reggeon $\mathcal{B}$ with trajectory $\alpha_{\mathcal{B}}(t)$. For forward events at HERA, $t \simeq 0$, and the fracture functions may be integrated over to increase statistics.

Although the Regge form is only an approximation to the more fundamental QCD description in terms of fracture functions, it shows clearly how observing semi-inclusive processes at large z, with particular choices of h and N, amounts in effect to performing inclusive DIS on virtual hadronic targets $\mathcal{B}$. For example, from the quark diagram in Fig. 3, we see that the reaction $ep \to e\pi^- X$ measures $g_1^{\mathcal{B}}$ for $\mathcal{B} = \Delta^{++}$.

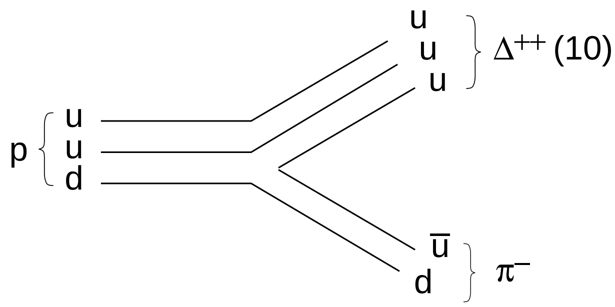

Fig.3 Quark diagram for the $Nh\mathcal{B}$ vertex in the reaction $ep \to e\pi^- X$ where $\mathcal{B}$ has the quantum numbers of Δ^{++}.

Since the suppression mechanism for topological charge depends only on the flavour structure of the exchanged object, we can make simple predictions for the ratios $\mathcal{R}$ of the first moments of the polarized fracture functions $\int_0^{1-z} dx\, \Delta M_1^{h/N}(x,z,t,Q^2)$ for various reactions. We emphasize that these do not depend on any detailed model of the fracture functions, such as single- or even multi-Reggeon exchange. The most interesting is [2]

$$\mathcal{R}\left(\frac{ep \to e\pi^- X}{en \to e\pi^+ X}\right) = \frac{2s+2}{2s-1} \tag{9}$$

for which we expect a clear difference from the naive quark counting (OZI) expectation of 4.

For strange mesons, the ratio depends on whether the exchanged object has $SU(3)$ quantum numbers in the **8** or **10** representation, so the prediction is less clear:

$$\begin{aligned}\mathcal{R}\left(\frac{ep \to eK^0 X}{en \to eK^+ X}\right) &= \frac{2s-1-3(2s+1)F^*/D^*}{2s-1-3(2s-1)F^*/D^*} \quad (\mathbf{8}) \\ &= \frac{2s+1}{2s-1} \quad (\mathbf{10})\,.\end{aligned} \tag{10}$$

Similar results can be given for charmed mesons. For example

$$\mathcal{R}\left(\frac{ep \to eD^- X}{en \to eD^0 X}\right) = \frac{2s+2}{2s-1}\,. \tag{11}$$

For $z \to 0$, these ratios all reduce to the first moment ratio of g_1^p/g_1^n. The expectation for the whole range $0 < z < 1$ is therefore as shown in the sketch of Fig. 4.

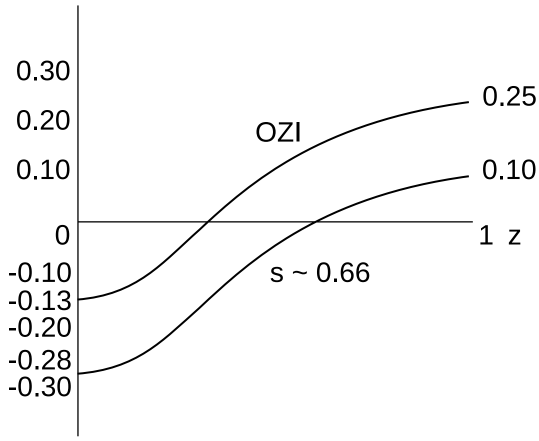

Fig.4 Cross-section ratios for $en \to e\pi^+(D^0)X$ over $ep \to e\pi^-(D^-)X$ between $z \to 0$ and $z \to 1$, contrasting the OZI and the target-independence predictions.

2 Target Fragmentation at Polarized HERA

In this section we summarize the most important experimental and phenomenological features of a measurement in the target fragmentation region, concentrating on the case of pion production.

It is worth noticing that the same features apply for ρ production, since the quantum numbers of the exchanged object are the same, and, indeed, for any non-strange meson with the same charge. Since the production of leading strange mesons from protons and neutrons is highly

[2] In these equations, a ratio of Wilson coefficients C_1^S/C_1^{NS} has been absorbed into the definition of $s(Q^2)$.

suppressed, the particle identification requirements will be less stringent than for pions alone. It is also important to emphasize that the predictions given here require dominance by the exchange of an object in the **10** representation of flavour $SU(3)$ over one with the same quantum numbers in the **27**, corresponding to disconnected quark diagrams (cf. Fig. 3) with 5-quark exchange. Assuming this, the predictions are expected to apply not only for values of z very close to 1, but for a more relaxed kinematical region of leading mesons, say $z > 0.6$. In any case, the z dependence of the ratio will also give very useful information about this mechanism.

In order to clarify the experimental situation it is useful to compare it with the well-known diffractive and leading protons and neutrons measurements already made by both HERA collaborations. Leading neutron production was measured by the ZEUS [7] and H1 [8] collaborations using a Forward Neutron Calorimeter (FNC), a lead scintillator calorimeter located about 100 m downstream of the interaction point, allowing the detection of very forward scattered neutral particles within about 1 mrad of the incident proton beam direction. Both collaborations found that about 10% of the DIS events contain a neutron in the forward region with more than half of the energy of the proton beam.

In the case of protons in the target fragmentation region, they are measured with the Leading Proton Spectrometer (LPS), consisting of detectors operating inside movable Roman pots located in the beam pipe, which measure the curvature of the charged particle and therefore its momentum. The ZEUS Collaboration [9] has measured the distribution of leading protons in the range of $z > 0.6$, analysing also the t dependence. This allowed a cleaner definition of the diffractive process in terms of fracture functions, i.e. as one where a proton carrying more than 97% of the momentum of the initial proton is detected in the final state, instead of the usual definition in terms of rapidity gaps. The H1 Collaboration [10] has measured the production of leading protons in the kinematical region of $0.7 < z < 0.9$ with enough accuracy to analyse the Q^2 dependence. The sample of data used corresponds to an integrated luminosity of about 1.44 pb^{-1}, to be compared with the maximum one expected in the polarized case of about 500 pb^{-1}.

The variables used in the different measurements are easily related to z, by $z = x_L$ for leading protons and $z = 1 - x_{I\!P}$ for diffractive scattering. In the same way, the defined leading proton, leading neutron and diffractive structure functions are just $M_2^{B/p}(x, z, Q^2) = \sum_i \hat{e}_i^2 x M_i^{B/p}(x, z, Q^2)$, the fracture function equivalent of the inclusive F_2, where B corresponds to either a proton or a neutron.

The acceptance of the LPS has been optimized for positively charged particles with an almost negligible one for negative hadrons, since proton measurement was the main objective and, up to now, there is no identification system available in the target region. An ID system would allow a precise measurement of charged mesons as needed in this proposal.

The acceptance of the LPS could in principle be extended in order to measure mainly negative hadrons by adding some extra stations. In that case it would be possible to obtain a very good approximation for the production of $M^- = \pi^-, \rho^-$ by the sensible assumption of its dominance over strange mesons and heavier hadrons, i.e. $\sigma(p \to h^-) \simeq \sigma(p \to M^-)$. Any remaining positive charged hadron contribution could be subtracted if the acceptance for both negative and positive hadrons were known.

The identification of positive mesons, needed for the process $n \to M^+$, seems to be the most complicated task, basically because the cross section will be dominated by the proton background.

Besides this, an additional problem comes from the fact that neutron beams are not available. They are fundamental in the construction of the ratio in eq. (9), which is independent of the unknown matrix elements appearing in each sum rule separately. The polarized HERA option for neutrons is ^{3}He. In that case, even for the polarized cross section, there is a contribution coming from the scattering of protons in ^{3}He, which has to be subtracted. Assuming for the sake of simplicity that ^{3}He is a simple combination of free protons and neutrons, i.e. schematically ^{3}He$=A\,p+B\,n$, the cross section for the production of positive hadrons measured in the LPS is given by

$$\sigma(^3\mathrm{He}\to h^+) \simeq A\,\sigma(p\to h^+) + B\,\sigma(n\to p) + B\,\sigma(n\to M^+)\,, \tag{12}$$

where the first contribution on the right-hand side can be obtained from measurements with the proton beam. In order to subtract the second one, it would be necessary at least to distinguish protons from mesons. In the region of very small x, where the singlet contribution dominates, it could be possible to use $SU(2)$ arguments to relate the cross section for the process $p\to n$, obtained with the existing FNC, to the corresponding one for $n\to p$, but the same argument fails for the non-singlet contribution.

It is possible to obtain a rough estimate of the fraction of DIS events containing one of these leading mesons by using a sensible model for the production of forward hadrons, as in the approach of ref. [11]. The idea there is to exploit the non-perturbative meson–baryon (MB) Fock components of the nucleon to compute the flux of the final state particle in the proton. This flux is normalized by the non-perturbative strong couplings known from low energy physics ($g^2_{pMB}/4\pi$) and with a parameter adjusted to describe the distribution of the produced B in hadron–hadron collisions.

In this approach, an expression for $M_2^{M/p}(x,z,Q^2)$ [12] can be written down:

$$M_2^{M/p}(x,z,Q^2) = \phi_{M/p}(z) F_2^B\left(\frac{x}{1-z},Q^2\right)\,, \tag{13}$$

i.e. the flux (in this case integrated over t) times the structure function of the exchanged object.

In ref. [11] the flux for $\phi_{\Delta^{++}/p}(z)$ was computed taking into account the exchange of both π and ρ. The flux needed in our case can be obtained from this by a simple crossing relation $\phi_{M/p}(z)=\phi_{B/p}(1-z)$, where $B=\Delta^{++}$. It turns out from the computation that at large z the production of ρ^- is expected to dominate over that of π^-, basically because a heavy meson will carry a larger fraction of the momentum of the MB state than the lighter one. In contrast to ref. [11], where the reggeization of the flux is not considered, we have also imposed an asymptotic behaviour of $(1-z)^{1-2\alpha_B(t)}$ with $\alpha_\Delta(0)\approx 0.0$, but its consequence is negligible since the flux in [11] already vanishes when $z\to 1$.

The structure function of the exchanged virtual Δ^{++} can be estimated using parton distributions in the proton [13]. Even though this approach does not have the same validity as in the case of an almost real pion exchange, such a model could also be useful in order to obtain sensible extrapolations of the fracture function in the unmeasured region, since some of the parameters of the model could be fitted to reproduce the results in the measured region.

Then the fraction of DIS events with either a π^- or a ρ^- in the target fragmentation region with $z>z_{min}$ is given by

$$\frac{d\sigma(ep\to e'MX)/dx\,dQ^2}{d\sigma(ep\to e'X)/dx\,dQ^2} = \frac{\int_{z_{min}}^{1-x} dz\, M_2^{M/p}(x,z,Q^2)}{F_2^p(x,Q^2)}\,. \tag{14}$$

This approach has been shown to work rather well for leading neutron production [12], but to underestimate the production of leading protons by almost a factor of 2 [10]. As a final result it is found that a fraction of between 0.5% and 1% of the DIS events will contain a leading meson in the target fragmentation region where the LPS has non-vanishing acceptance ($z>0.6$) and in the dominant $x < 0.1$ domain. Most of them, as expected, correspond to the lower values of z and the ratio decreases for larger x. This prediction for the rate of meson production can be tested by using the unpolarized proton beam.

The experimental analysis of the semi-inclusive polarized cross section can be done in the same way as for the inclusive one containing g_1, since the expressions for the cross sections (as in (6)) corresponding to structure and fracture functions are completely equivalent. In this case, a sub-sample of the DIS events, where a leading particle with a fraction of momentum z is detected has to be used for the analysis. For leading protons and neutrons the corresponding sample of events showed the same rapidity gap features as the full sample; the same can thus be expected for this measurement, in contrast to the diffractive case where large rapidity gaps are observed.

3 Summary and Conclusions

We have described experiments that would test the idea of universal topological charge screening as the mechanism underlying the 'proton spin' effect. Obviously, many of the experimental requirements described above involve difficult technical problems, which remain to be solved. In particular, the identification of mesons in the LPS region seems to be the most complicated task, together with the extension of the LPS acceptance in order to measure negative particles. Furthermore, the proposed observable includes the production of positively charged mesons from a polarized neutron beam, which could be obtained from the polarized ^{3}He measurement.

Nevertheless, target fragmentation studies can provide a key to understanding some very fundamental aspects of QCD, and would be a valuable part of the experimental programme at polarized HERA, which, we want to stress, would be the only experimental facility available to study these particular processes.

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