SPIN STRUCTURE AT THE PARTONIC LEVEL

II QCD TESTS IN HADRONIC REACTIONS

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ABSTRACT

Knowledge of the spin and momentum distribution of partons inside a polarised nucleon, as deduced from lepton scattering, is combined with lowest order QCD to calculate spin dependent parameters in large p_T hadronic reactions. Clear predictions emerge in some cases and are in conflict with present experimental results. There is a real challenge to improve both theory and experiment.

1. INTRODUCTION

The crucial information that can be learnt about the fundamental internal structure of hadrons from deep inelastic lepton scattering with polarised beams and targets, as discussed in I in this volume,*) is here utilised in studying spin dependent phenomena in hadronic reactions. We thus assume that we have some knowledge of the distribution in momentum and spin of the partons inside a polarised hadron and use perturbative QCD to predict the behaviour of spin dependent observables in various kinds of large p_T hadronic reactions.

We stress that the spin-structure of QCD, at a perturbative level, is very simple and precise, so that clean and restrictive predictions emerge that can be used to test the basic validity of the theory. Indeed, it should be remembered, that although QCD is intuitively and aesthetically seductive, there is really very little concrete evidence in its favour. Tests, therefore of its detailed coupling-structure are very important. Since, however, we are only able to do perturbative calculations, it is essential to study reactions in those kinematic regions (usually high energy, large p_T) where there is some chance of these being valid. It is also important to remember that the actual polarising power P is only one of many spin-dependent parameters, and one may well have P=0 and, at the same time, important spin effects.

In the following we shall talk at the level of the simplest parton picture used in conjunction with lowest order QCD. It is expected, though not rigorously demonstrated, that higher order QCD effects will only minimimally affect the spin-dependent observables (see contribution by Craigie). In this picture the polarised beam and polarised target simply act as the sources of wide-band polarised parton beams which then interact via lowest order QCD. This is illustrated below for an inclusive reaction $A+B\to C+X$

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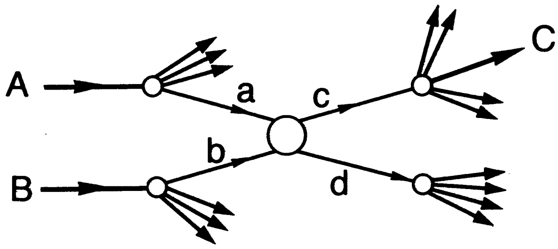
*) See page 23.



2. INCLUSIVE REACTIONS : A+B→C+X

If, for example, A and B are fully polarised with helicities λ_A, λ_B one one has the generic formula :

$$d\sigma_{\lambda_A \lambda_B} \propto \sum_{\substack{\text{Helicity}\\ \lambda,\lambda'}} \sum_{\substack{\text{Flavours}\\ a,b,c.}} \int dx_a dx_b \, G^{a,\lambda}_{A,\lambda_A}(x_a) \, G^{b,\lambda'}_{B,\lambda_B}(x_b) \, D^C_c(z) d\hat{\sigma}_{\lambda\lambda'} \quad \ldots \quad (1)$$

where $G^{a,\lambda}_{A,\lambda_A}(x_a)$ is the number density of flavour "a" partons of helicity λ and momentum fraction x_a to be found in hadron A of helicity λ_A, etc., and $d\hat{\sigma}_{\lambda\lambda'}$ is the lowest order QCD cross-section for the parton reaction a+b→c+x starting with partons of helicity λ and λ'. For valence quarks the G functions are presumed known from deep inelastic lepton scattering while for sea quarks and gluons, models have to be constructed. This should not be a source of great uncertainty provided one keeps to kinematic regions where the valence quarks dominate.

A most important characteristic feature of QCD is that the helicity of a fast quark is unchanged during the reaction. It then follows that if only the beam or only the target is polarised, or if one measures the polarisation of C for an unpolarised beam and target, one should get zero. In other words:

All single-spin asymmetries = 0 ... (2)

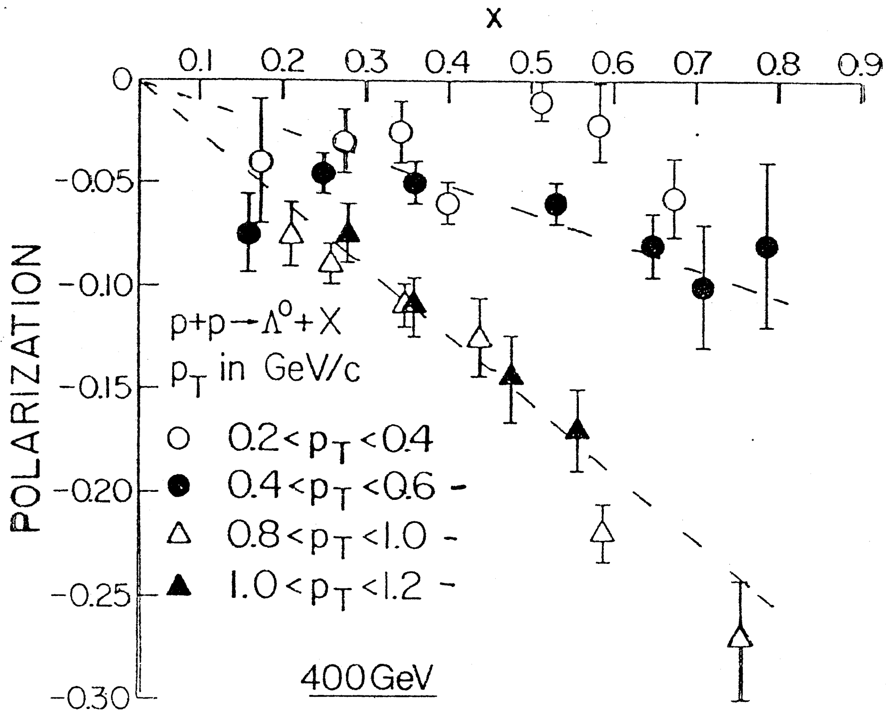
The experimental situation is fascinating.

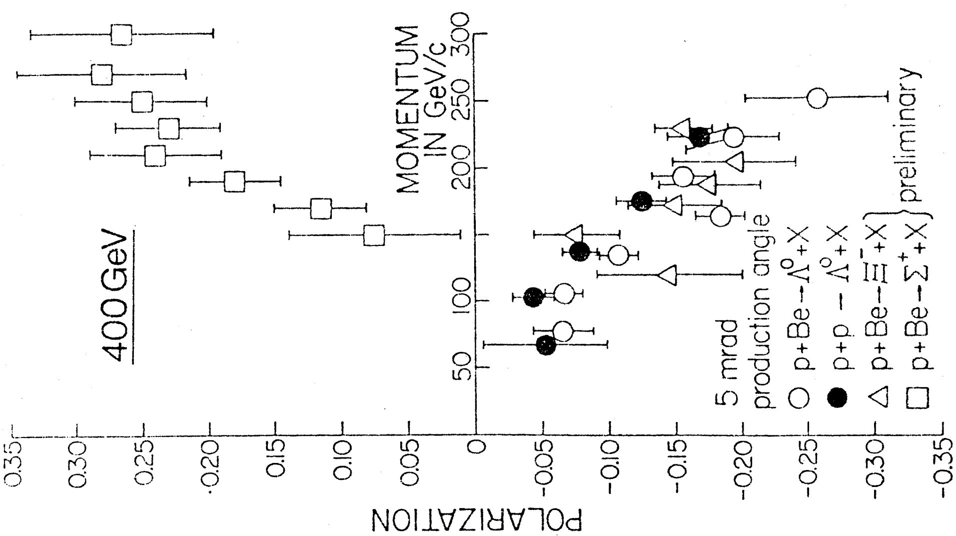
a) <u>Unpolarised beam and target</u> : The reactions

pp→hyperon + X

wherein the hyperon is self-analysing have been studied for $\Lambda, \bar{\Lambda}, \Xi^-$ and Σ^+.

All except $\overline{\Lambda}$ have significant polarisations (20-30%), and for Λ this has been shown to be true all the way from PS to ISR energies. The p_T involved ($\lesssim$3 GeV/c) could be considered to be too small to trust perturbative QCD, but there is no sign of any decrease in the polarisation as P_T increases, nor any sign of energy dependence. Some feeling for the data[1] can be obtained from the figures below.





There are several somewhat ad hoc models designed to explain these features[2]. None are very fundamental and all predict P→0 as p_T increases.

Measurements at larger p_T , and in $p\bar{p}$ collisions (especially of $\bar{\Lambda}$ polarisation) are vitally needed.

b) <u>Polarised Target only</u> : The reaction $p\vec{p} \to \pi^0 X$ shows an asymmetry of about 30% at all measured energies[3]. The asymmetry is zero according to lowest order QCD. Again the escape clause is that p_T is not large enough. Tests at larger p_T must be carried out!

c) <u>Polarised Beam and Target</u>. Various asymmetries in $\vec{A}\vec{B} \to CX$ are possible with polarisations either longitudinal (L), transverse (S) in, or normal (N) to, the ABC plane. All are non-zero in lowest order QCD and, indeed, are sometimes very large at the partonic level, but the latter get diluted because the partons in a 100% polarised hadron beam are not themselves fully polarised. Nonetheless significant and measurable asymmetres are predicted.

The theoretical formulae are quite transparent. For example, for longitudinal polarisations of beam and target one has

$$\frac{d\sigma(\vec{A}\vec{B}\to CX) - d\sigma(\vec{A}\overleftarrow{B}\to CX)}{d\sigma(\vec{A}\vec{B}\to CX) + d\sigma(\vec{A}\overleftarrow{B}\to CX)} =$$

$$= \frac{\sum\!\!\int [q^{\mathcal{P}}(x_a) - q^{\mathcal{A}}(x_a)]_A \, [q^{\mathcal{P}}(x_b) - q^{\mathcal{A}}(x_b)]_B \left\{ d\hat{\sigma}^{\rightrightarrows} - d\hat{\sigma}^{\rightleftarrows} \right\}_{ab\to cX} D_c^C(z)}{\sum\!\!\int \underset{A}{q(x_a)} \; \underset{B}{q(x_b)} \left\{ d\hat{\sigma}^{\rightrightarrows} + d\hat{\sigma}^{\rightleftarrows} \right\}_{ab\to cX} D_c^C(z)} \qquad \ldots (3)$$

where the sum is over flavours and the integral over x_a, x_b. The number densities $q^{\mathcal{P}}$, $q^{\mathcal{A}}$ of partons with spin parallel or anti-parallel to the parent hadron's spin were defined in I, eqn.(1).

If we ignore the effects of the smearing due to the momentum integration and flavour sum, we get a remarkably simple and intuitive result :

$$A_{LL}^{\text{Hadronic}} \simeq \langle\hat{P}\rangle_A \, \langle\hat{P}\rangle_B \, \hat{A}_{LL}^{\text{Partonic}} \qquad \ldots (4)$$

where e.g. $\langle\hat{P}\rangle_A$ is the average polarisation of the partons in hadron A , $\hat{P}$ itself being defined by

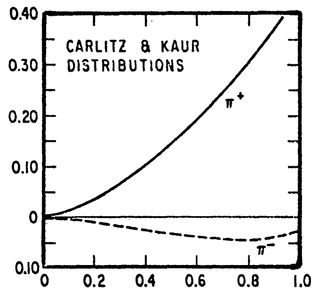
$$\hat{P} = \frac{q^{\mathcal{P}}(x) - q^{\mathcal{A}}(x)}{q^{\mathcal{P}}(x) + q^{\mathcal{A}}(x)} = \frac{q^{\mathcal{P}}(x) - q^{\mathcal{A}}(x)}{q(x)} \qquad \ldots (5)$$

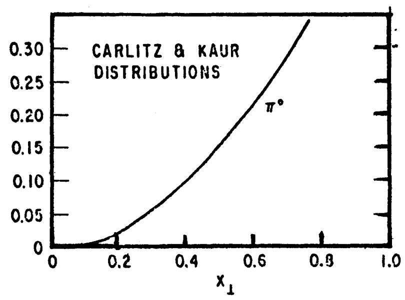
the last step following from I eqn.(1), and the partonic $\hat{A}_{LL}$ is

$$\hat{A}_{LL} = \left\{ \frac{d\hat{\sigma}^{\rightrightarrows} - d\hat{\sigma}^{\rightleftarrows}}{d\hat{\sigma}^{\rightrightarrows} + d\hat{\sigma}^{\rightleftarrows}} \right\}_{ab\to cX} \qquad \ldots (6)$$

Eqn.(4) could be a little dangerous, since the $\hat{A}_{LL}$ vary considerably[4] for qq, $q\bar{q}$, qg, gg etc., but numerical calculations show it to give a correct order of magnitude estimate.

To get some feeling for the magnitudes we show below the results[4)] for A_{LL} for $pp\to\pi^{o}X$ and $pp\to\pi^{\pm}X$, computed using the Carlitz-Kaur parton number densities which were discussed in I.





Detailed predictions can be found in ref.(4). A_{LL} is clearly large enough to measure. Generally A_{NN} comes out much smaller.

$$A_{NN} \simeq 10^{-3}A_{LL} \qquad \ldots(7)$$

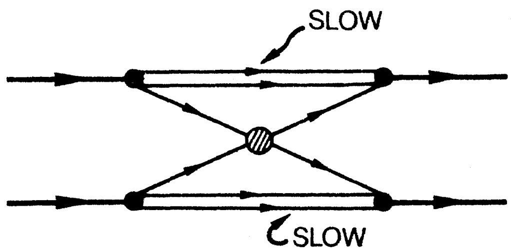
and so might be impossibly difficult to pin down. We conclude that measurements with longitudinal polarisations will provide a very interesting test of the whole picture.

3. EXCLUSIVE REACTIONS AT LARGE p_T

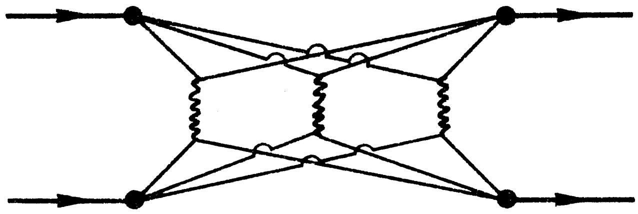
Exclusive reactions, such as $pp\to pp$ at large p_T, are much more difficult theoretically because several different mechanisms could be important even within the framework of the simple parton model and lowest order QCD. It could then happen that one particular mechanism dominated the differential cross-section whereas a different one is responsible for the main spin correlation. In such a situation it is meaningless to compute spin asymmetrics from either one mechanism alone. The problem is exacerbated by the fact that the relative normalisation of the various contributions is usually unknown, so they cannot just be added together.

There are three main types of contribution, illustrated below.

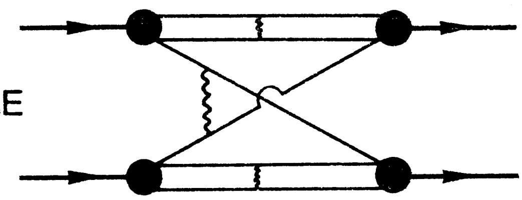
END POINT



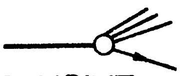
LANDSHOFF



BRODSKY-LEPAGE

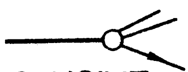


It should be realised that the hadron vertices which look so similar in the inclusive and exclusive diagrams, are really quite different, as is indicated schematically below :



INCLUSIVE

$$= \sum_n \int dx_2 \cdots dx_n \left| \psi(x, x_2 \cdots x_n) \right|^2$$



EXCLUSIVE

$$= \psi(x_1, x_2, x_3)$$

What distinguishes the mechanisms is that in the "end point" diagrams of Szwed[5)] and Preparata[6)] only one quark gets a large p_T kick, whereas in the "Landshoff"[7)] or "Brodsky-Lepage"[8)] diagrams all quarks share the p_T. For large p_T the "end-point' mechanism can only be important when x of the active quark is close to 1. But outside this region one expects the "Landshoff" mechanism to dominate, though it is now believed that these contributions may be suppressed by so-called Sudhakov factors[9)], and, in the end, the "Brodsky-Lepage" diagrams might control the large p_T differential cross-section.

We are convinced that all mechanisms are important for spin effects, and that it is therefore difficult to make precise numerical predictions. Nevertheless, <u>all</u> mechanisms have P=0, so it appears to be an unambigious prediction that

$$P = 0 \qquad \ldots (8)$$

for large p_T elastic or two-body scattering.

The two-spin correlation parameters are non-zero in all mechanisms, but their values depend upon which diagram one takes, and since, e.g.

$$A_{NN}^{total} \neq \sum_i A_{NN}^{i^{th} diagram}$$

it is a little meaningless to quote results. Nonetheless, we indicate briefly what is found for the nucleon-nucleon helicity amplitudes ϕ_j (j=1..5) and for some of the spin parameters:-

Szwed: $\begin{cases} \text{Only} \quad \phi_5 = 0 \\ A_{NN} \simeq 0\cdot5 \text{ to } 0\cdot7; \quad A_{LL} \simeq -0\cdot3 \text{ to } -0\cdot5 \end{cases}$

Brodsky-Lepage: $\begin{cases} \therefore \phi_2 = \phi_5 = 0 \\ \therefore A_{NN} = -A_{SS}. \\ \text{In any reaction} \quad \Sigma\lambda_i = \Sigma\lambda_f \end{cases}$

the sum being over the initial (i) and final (f) hadron helicities.

4. CONCLUSIONS:

We believe that the spin dependent data in hadronic reaction presents a great challenge to both theorists and experimentalists. Taken literally the present data is in contradiction with perturbative QCD and the parton model. But we have an uneasy feeling that the theoretical treatments are too naive and it is vitally important for the experamentalists to plunge ahead and establish firmly what exactly is happening, especially at larger values of p_T. Do the single spin asymmetries vanish?

Finally, although it has nothing to do with large p_T, we cannot help reminding our experimental colleagues of the classic reaction $\pi^- p \to \pi^o n$ and of the cataclysmic role played by its polarisation measurements in destroying theories in the past. We still do not know whether the Pomeron has an odd-signatured twin (the Odderon[10]), small in magnitude but very different in phase. A measurement of P in $\pi^- p \to \pi^o n$ at SPS energies could settle this once and for all.

REFERENCES

1) The most recent publication is Bensinger et al, Phys. Rev. Letts. 50, 313(1983) from which earlier references may be traced.

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3) J. Antille et. al. Phys. Letts. 94B, 523(1980)

4) J. Babcock, E. Monsay, D. Sivers, Phys. Rev. D19 1483(1979)

5) J. Szwed, "Spin Effects in Hadronic Collisions at Large Momentum Transfers", Jagellonian University, Krakow, preprint TPJU - 1/82, March 1982.

6) G. Preparata and J. Soffer, Phys. Lett. 86B, 304(1979).

7) P.V. Landshoff, Phys. Rev. D10, 1024(1974)

8) See e.g. S.J. Brodsky and G.P. Lepage, Proc. Intl. Symp. on Pold. Beams and Pold. Targets, eds. C. Joseph and J. Soffer, Lausanne 1980.

9) A.H. Mueller, Phys. Rep. 73, No4, 237(1981)

10) For a recent review, see B. Nicolescu : "The New ISR and Collider $\bar{p}p$ and pp Data and Asymptotic Theorems" ORSAY preprint IPNO/TH 82-46, October 1982.