Symposium Summary*

Philip G. Ratcliffe

*Istituto di Scienze, Università di Como, via Lucini 3, 22100 Como, Italy
and Istituto Nazionale di Fisica Nucleare – Sezione di Milano

ABSTRACT

The plenary presentations of the conference are summarised, highlighting some aspects that were of particular interest and attempting to link a few of the topics covered. Particular emphasis is placed on the problem of deep-inelastic scattering and questions still to be answered with regard to the distribution functions, strange-quark and gluon contributions, and the possible rôle of orbital angular momentum. Passing reference is also made to some of the parallel session presentations.

Introduction

Let me begin by apologising for the only scant coverage that I can make of all the numerous and interesting parallel presentations; the human lack of ubiquity being what it is, I could attend only one of any of the five contemporary sessions. Thus, in order to be fair on those speakers I did not hear, I shall make no direct references to the parallel talks and limit myself to oblique citation only. I should also point out that I am not an experimentalist and am therefore not qualified to discuss detector details etc. On the other hand, nor shall I present any of the particularly formal theoretical aspects. These may, of course, be found in the write-ups of the originals elsewhere in this volume.

As usual in this series of symposia, the parallel-session presentations ranged from accelerator physics to polarised sources and from detectors to phenomenology and theory, with a good deal of overlap. The physics issues involved cover the full extent of the Standard Model, including both electro-weak and strong-interaction theory. However, the large amount of effort being spent on the problem of polarised deep-inelastic scattering and the related structure functions was particularly noticeable: approximately a third of the talks, both plenary and parallel, had to do specifically with this topic and an even larger part was indirectly connected. As my own interests lie very much in the this area, the same bias will be amply reflected here; I apologise to those whose preferences lie elsewhere and refer them to the other contributions reported in these proceedings.

For the sake of brevity and space, I shall only provide full references to works not reported herein; talks presented at the conference will be simply referred to by the authors' names. In the same spirit, I shall also refrain from the repetition of formulæ and listing of experimental data.

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Polarised Structure Functions
A Very Brief History
A rather complete account of the theoretical basis for discussing the nucleon spin structure can be found in [1]. The history of this subject can be said to start in 1966 with the pioneering work of Bjorken [2]: although not based on the modern theory of Quantum Chromodynamics or even the Quark-Parton Model, this paper nevertheless set up a framework for phenomenological sum rules based on current algebra. Thus, a benchmark for experimental measurement was erected, together with a starting point for theoretical predictions based on the more sophisticated approach of perturbative QCD (for details see J. Ellis and S. Forte in this volume). The historical value of the Bjorken sum rule is encapsulated in Feynman’s now celebrated statement that

“... its verification, or failure, would have a most decisive effect on the direction of future high-energy physics.”

As it stands, the BJ sum rule requires the measurement of both the proton and neutron spin structure functions. Thus, in order to render it more experimentally accessible, in 1974 two young researchers took the liberty of a simplifying assumption to cut it in half and obtain sum rules for the proton and neutron separately [3]; after considering various possibilities, the nomenclature EJ was finally settled upon:

\[ \int_0^1 d\xi \left( q_1 - q_2 \right) = \frac{1}{12} q_A + \frac{5}{36} q_8 \approx 0.19 \]

Note that the PQCD corrections are an order 10% effect at typical experimental energies. Thus, it was indeed a great surprise to most when in 1988 the EMC experiment announced a value [4] that was little more than half the original EJ prediction. However, with hindsight, one might claim that there was nothing cast-iron about the assumption made and so the deviation led to the following somewhat sacrilegious paraphrasing of Feynman’s words:

“... the verification, or failure of the EJ sum rule, would have a most indecisive effect on the direction of future high-energy physics.”

The questions raised by this discovery were manifold, ranging in gravity from the reliability of the low-energy \( F \) and \( D \) parameters to a possible failure of PQCD; certainly the EJ assumption was thrown into doubt but equally the possibilities arose of, e.g., orbital angular momentum contributions, and large gluon or strange-quark

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1 Reproduction of a notebook fragment of uncertain origins (c. 1974) now preserved in the SLAC historical archives—unfortunately, the authors’ names have long since been rendered illegible.

2 Anonymous graffiti found on numerous blackboards.
polarisations. All these questions have stimulated research that has undoubtedly led to a deeper insight into the structure of the proton and to a greater interest in the subject experimentally. In any case, it is now perhaps time to try and set the records straight:

“The very existence of the BJ sum rule has already had a most decisive effect on the . . . ”

while

“The failure of the infamous EJ sum rule has also had a most decisive effect on the . . . ”

The former as a spur to investigating the field and the latter as witnessed by the tremendous effort that has been made in recent years to understand this problem.

Hyperon Semi-Leptonic Decays
At this point I shall avail myself of the summary speaker’s prerogative and take the opportunity to touch briefly upon a problem not explicitly discussed during the conference but that is nevertheless of some importance in the analysis of nucleon spin sum rules: namely, the input coming from the analysis of the hyperon semi-leptonic decays.

While the BJ sum rule only requires knowledge of the neutron $\beta$-decay constant $(g_A/g_V = F + D)$, the EJ sum rule for either proton or neutron necessitates the input of both the SU(3) parameters $F$ and $D$ separately. The various axial couplings responsible for the decays of other octet baryon states, depending on different linear combinations, allow just that, providing one knows how to handle the problem of SU(3) violations. Most authors either simply accept one of the “standard” published sets of values (more-or-less tacitly) and thus make the usual deduction that the quarks carry little of the proton spin, or via often ad hoc and almost always highly model-dependent analyses find very different values that can then accommodate the EMC (and subsequent) results at no further expense.

Since the deductions made as to, e.g., the strange quark polarisation can vary considerably, it is worth while stressing here that the only completely consistent analysis performed (based on purely relativistic corrections) on all of the most up-to-date data produces a value [5]:

$$F/D = 0.57 \pm 0.01,$$

with a more than acceptable goodness of fit and agreement with other evaluations of related Standard Model parameters. Thus, it is now clear that, with present-day precision, relativistic corrections are both necessary and sufficient. That said, and especially in view of the ever-increasing experimental precision with which the sum rules are measured (see G. Mallot’s talk), there is still plenty of room for improvement, both experimentally and theoretically.
Parton Orbital Angular Momentum
Returning to issues concerning the proton spin structure more directly: a contribu-
tion that rightly aroused great interest, as a new handle on this problem, was that
by X. Ji on the inclusion of orbital angular momentum into the parton picture of
the nucleon and its possible experimental detection. The problem is an old one al-
though, until now, almost untouched in the standard formalism based on the parton
model and PQCD. On the other hand, if the so-called “gluon anomaly” explanation
of the EJ sum rule failure contains something of the truth, then there must be a
large orbital angular-momentum contribution, compensating that of the gluon helic-
ity. Thus, it is natural to ask how such a contribution might be dealt with formally
and whether or not it could have any, more direct, phenomenological consequences.

In relation to the problem of $Q^2$ evolution (à la GLAP), it has been known for
some time that at some energy scale a large orbital angular-momentum component
will be generated radiatively [6]. X. Ji has now completely formalised this observation
by defining all the relevant quark and gluon operators and by relating their matrix
elements to those of the energy-momentum tensor. He then suggests that they may
be accessible in a process he defines as “deeply-virtual” Compton scattering. Should
this be realisable in practice, the door would open into an entirely new field of parton
distribution measurements: namely, orbital angular-momentum densities.

Deep-Inelastic Scattering Data and Analysis
For those who prefer the concreteness of results already “under the belt”, let me
now examine the present experimental situation, as illustrated by G. Mallot and
discussed from the theoretical point of view by J. Ellis, J.C. Collins and S. Forte.
The precision with which the nucleon spin structure function $g_1$ is now measured
at the 3–4% level (taking the BJ sum rule value of $\sim0.17$ as a benchmark). As a
sign of the subject’s maturity, recall that even relatively recently the goal for the
unpolarised structure functions was still said to be a 10% accuracy [7]. Indeed, here
J. Ellis pointed out that the value for $\alpha_s$ extracted from the BJ sum rule is now highly
competitive with those from other sources. Moreover, S. Forte demonstrated that,
from the scaling violations alone, one is also beginning to acquire some sensitivity to
the size of the gluon polarisation in the nucleon, which was quoted as $\Delta G = 1.0\pm0.4$
(for $Q^2 = 1 \text{ GeV}^2$).

The SMC (CERN) and SLAC groups have both moved on to measuring other
quantities besides $g_1$: e.g., $\Delta q$, $g_2$, higher twist, etc. And, of course, we still have
more data to look forward to, including those of the Hermes collaboration at HERA.
In the case of the transverse spin structure function, $g_2$, one now has the precision
required to observe possible deviations from the Wandzura-Wilczek sum rule (again
based on certain plausible but far-from guaranteed assumptions [8]); and there may
already even be some indications in this direction in the preliminary neutron data.
As echoed by many speakers, J. Collins also mentioned the rôle that transverse spin
can play, particularly in the quest for understanding non-perturbative and chiral-
symmetry breaking effects.
Remaining Questions and Future Directions

There are several areas that merit further attention and that are, in fact, all essentially on the agenda:

a) Higher Twist — We are now beginning to get a handle on this sticky subject (see the SLAC analysis of their low-$Q^2$ data). The importance of this problem is clearly twofold: firstly, one would like to have such contributions under control to improve the reliability of the structure function analyses, and secondly, it is a study of interest in its own right, where spin, with its intimate links to chiral symmetry, can play an important rôle. This is an area in which the Hermes collaboration can also provide some clues.

b) Low-$x$ Extrapolation — Here one should perhaps give credit to Close and Roberts for their insistence on this point [9]. Although perhaps premature to abandon the asymptotic predictions of Regge theory entirely, one should clearly tread carefully, especially in the light of the unpolarised HERA data. Moreover, the resummation of the $\log x$ terms may be rather more subtle in the polarised case. The answers to these questions could most obviously be sought at a polarised HERA (see the talk by A. Schäfer).

c) Flavour Separation — Purely fully inclusive DIS cannot separate the various flavour contributions; the valence distributions can be isolated with some degree of precision but the sea quarks are not easily accessible. Since it is precisely to the sea quarks (i.e., strange quarks) that the EJ sum rule discrepancy is attributed (whether it be intrinsically or via the anomaly), a better handle on this sector is of some urgency. While the SMC is providing some information in this direction via semi-inclusive data, a better facility for such study will be provided by RHIC (see the talks by Y. Makdisi and H. En’yo). There one will be able to measure the distributions separately via the study of $W^\pm$ production in different kinematic regions.

d) Gluon Spin — While DIS scaling violations can give some information on the magnitude of the gluon polarisation, complete details and precision require the study of such processes as direct photon production (as will be measured at RHIC), which should provide important shape information. Again, a polarised HERA could reduce the present error on the size of $\Delta G$ via its larger $Q^2$ lever-arm and polarised proton beam on a polarised hadronic target, as discussed by A. Schäfer, could also give access to the shape.

The developments at RHIC were discussed in the two talks by Y. Makdisi and H. En’yo, who indicated the possibilities of measuring such quantities as the gluon polarisation and separating the flavour contributions, and underlined the complementarity to lepton-hadron scattering experiments at CERN, SLAC, HERA and CEBAF. The advantages of this machine are clearly its high luminosity and beam polarisation, which coupled to the energy range available will provide access to the
medium-$x$ range (where the polarised structure functions are large). The possibility of spin rotators will also allow measurements of the various transverse-spin structure functions (including transversity).

Low-$x$ Extrapolation
Before closing this long section on DIS I shall briefly examine a problem, already touched upon, that is of interest both theoretically and in connection with data analysis: namely, the problem of the small-$x$ behaviour. It is perhaps worth spending a few words to underline the importance of a correct treatment of this aspect, particularly in view of the important differences with respect to the unpolarised case.

As evident from the analyses presented by S. Forte, theoretical deduction from experimentally observed behaviour in polarised measurements is far less simple than one might be led to imagine, based on experience and knowledge of the unpolarised phenomenology. At the risk of over-simplifying, the source of the difficulties may be said to reside in the non-positivity of the spin distributions. The point is then that while the unpolarised distributions behave essentially monotonically with $Q^2$ (i.e., $F_2$ increases at small $x$ and decreases at large $x$ for increasing $Q^2$, owing to the Bremsstrahlung driving a degradation of the momentum distributions), the polarised distributions may have a much richer behaviour owing to cancellations of the various positive and negative contributions.

Moreover, whereas $F_2$ is already dominated by the sea (alias the Pomeron) for $x$ below $\sim 0.1$ say, the same is far from being true for $g_1$, as witnessed by the opposite signs of $g_1^p$ and $g_1^n$ in this region. This means, in particular, that extrapolation from the present values of $x$ (even those of the SMC) will be highly model dependent, the error introduced depending on the extremity of the limiting behaviour one is willing (or desirous) to admit. Moreover, it is not obvious at what values of $x$ (if any) one can reasonably expect (without the advantage of hindsight) that the extrapolation should become unambiguous.

At this conference some note was taken of the present trend in the neutron data in the small-$x$ region, which appear well described with a form of a simple (albeit large) power:

$$g_1^n(x) \sim -0.02 \frac{x}{x^{0.8}}.$$

Such a behaviour, if extrapolated to zero, could more than double the present estimates for the integral of $g_1^n$. This is, however, very misleading; a form such as

$$g_1^n(x) \sim -0.07 \frac{x}{x^{0.5}}(1 - 4x),$$

which gives a very good description of the data over a limited region, would give a contribution much more in line with the standard estimates.

In other words: cancellations between two relatively positive and negative contributions (one growing and one falling) can mimic even highly divergent behaviour over any finite range of $x$. 
Single-Spin Asymmetries

Let me now turn to an age-old problem in hadronic physics: that of the large (transverse) single-spin effects observed in hadron-hadron scattering, even at the large energies and the relatively large momentum transfers presently accessible. Once more we were treated to K. Heller’s customary talk on a subject that has been troubling phenomenologists now for approximately two decades. There are essentially two distinct experimental situations in which such phenomena are observed:

- hyperons produced semi-inclusively in hadron-hadron collisions are polarised along the normal to the production plane,
- mesons are produced asymmetrically (left-right) with respect to the plane defined by the beam-axis and the (transverse) polarisation direction in semi-inclusive (singly) polarised hadron-hadron scattering.

The basic puzzle lies in the fact that descriptions, either in terms of the “complicated” interplay of many amplitudes or “simple” hard partonic scattering, naturally lead to negligible effects. The former owing to cancellations between uncorrelated amplitudes and the second because the necessary spin-flip and imaginary phase are not generated in naïve massless PQCD tree diagrams. On the other hand these phenomena are rendered all the more interesting by the regularities displayed; the asymmetries (typically of the order of a few tens of percent):

- increase with $x_F$,
- increase with $p_T$ (up to about 1 GeV),
- obey simple SU(6) relations with regard to signs,
- are approximately energy independent.

And while many models are able to explain some of the effects, there are certain irregularities not all explicable in any given model:

- $P_{\Xi^{-}}$ increases with energy,
- $P_{\Sigma^{+}}$ decreases with energy,
- $P_{\Xi^{-}}$ does not increase with $x_F$,
- $P_{\Xi^{-}}$ and $P_{\Sigma^{+}}$ are non-zero.

The attitude of the “non-spin” physicist might be summed up as assuming that such effects will eventually go away for large enough transferred momenta (where PQCD should correctly describe the dominant contributions) and that in any case the phenomenology is too complex to be of interest. As a counter to this, first of all, note that the regularities described above are very suggestive of simple mechanisms
while the few irregularities and possible disappearance of polarisation at large $p_T$ only serve to enhance the importance of understanding such processes. In particular, the point at which the hard dynamics really takes over could provide vital information on the strength and rôle of the sub-asymptotic and/or non-perturbative dynamics and, in this specific case, possible indications as to the rôle of chiral symmetry breaking. Moreover, there is also the eventuality of the effects resisting unabated (as they still do) even up to typically “perturbative” scales, thus posing a question that could no longer then be simply ignored.

**Weak Interactions as Probes of Spin Structure and New Physics**

There are a number of the physics issues that can be addressed via the use of weak interactions: these include, besides the obvious Standard Model physics, the search for new physics and also an alternative approach to hadronic matrix elements related to those measured in polarised DIS.

In the search for new physics, and this was exemplified by M. Musolf in terms of a possible new $Z^0$ (or $Z'$) and/or effect four-fermion couplings, the different helicity structures likely to be exhibited would provide unambiguous signals. In this respect, it should always be remembered that at the elementary level many polarisation asymmetries are naturally of the order of 100%, especially in the high-energy limit where masses and thus spin-flip may be neglected. The fact that they change dramatically (even sign) for new interactions (viz. supersymmetry) renders them highly sensitive to the onset of new energy scales and related physics.

Thus, a modest improvement in the measurement of say $A_{LR}(0^+, 0)$ in nuclear scattering to the level of 1% would push the lower limits on the mass of a $Z'$ and the scale of compositeness up to 0.9 TeV and 16 TeV respectively.

The so-called “oblique” corrections to boson exchange can also lead to sensitivity to new physics: these are usually parametrised via the $S$ and $T$ parameters. Low-energy experiments are typically more sensitive to $S$ and the present level of sensitivity is only just short of revealing possible deviations from zero.

Measurements involving electro-weak interactions can also provide access to hadronic currents not accessible with purely electromagnetic probes: in particular the vector and axial-vector couplings of the $Z$ boson provide a third combination of up, down and strange currents thus allowing a measurement of the strange contribution to proton matrix elements. B. Beise, reporting on preliminary results from the MIT/Bates experiment SAMPLE, presented a measurement of the strange magnetic moment $\mu_s$ for the nucleon. The first indications appear to be for a small (of a similar magnitude to the predictions) but positive value; within errors it is, however, compatible with zero. The theoretical estimates for this quantity vary widely; however, they are generally negative. There are a number of theoretical approaches to the problem, all having in common the need to generate strange-quark loops. This has been done in calculations based on $K$-meson clouds, VMD poles, the constituent QPM, the Skyrme model, bag models, etc. It is hoped to take more data in 1997 and so we might look forward to serious testing of these theoretical models.
Polarised Electrons
Spin is now becoming a fact of life in storage rings: the natural polarisation, due to the Ternov-Sokolov effect \cite{10}, has a maximum theoretical value of 92.4\% and, in practice, the polarisations obtained now are not far below. In his account of progress in polarised electron beams, D. Barber underlined that already at HERA polarised positron beams of around 70\% had been maintained for up to ten hours and that in the future one can hope for as much as 80\%.

An example demonstrating the day-to-day importance of spin is the use of polarised beams at LEP, where the polarisation is typically between 5 and 10\% (although it should be remembered that 57\% was achieved in 1993). Using a one gauss-metre radial magnetic field an energy calibration at the MeV level has been attained ($\Delta M_Z \simeq 1.5$ MeV and $\Delta \Gamma_Z \simeq 1.7$ MeV).

Finally, D. Barber was at pains to stress the need for advanced planning: polarisation cannot be an afterthought; the possibility has to be at least allowed for at the design stage in order to avoid the risk of its total preclusion.

Linear colliders have also progressed far in respect of spin physics: results of the SLD collaboration at SLAC were presented by R. Prepost, who particularly emphasised the rôle of the machine as a predominantly polarised facility, with a beam polarisation approaching 80\%. Measurements of the left-right asymmetry $A_{LR}$ contribute decisively to an increased precision in $\sin^2\theta_W^{\text{eff}}$. He also discussed the importance of Ring Imaging Čerenkov Detectors in heavy quark measurements (e.g., $A_c$ and $A_b$) and stressed the importance of polarisation in separating $B$ versus $\bar{B}$ production in the study of $B$-$\bar{B}$ mixing.

Medium- and Low-Energy Hadron Spin Physics
S. Vigdor summarised possible tests of symmetry principles accessible in medium-energy hadron physics, such as T-violation in $\vec{p} - \vec{d}$, which is under consideration at COSY in Jülich. This would be the first experiment to use a recently proposed technique to measure $\Delta \sigma_{\text{tot}}$ (spin) via the spin dependence of the stored beam lifetime. Charge-symmetry breaking effects in nuclear forces (i.e., non-invariance under $u \leftrightarrow d$) can also be usefully investigated with the use of polarisation. Here the proposed IUCF search would use polarisation as a filter for rare processes.

The use of $\vec{p}$ beam (target) and $\vec{d}$ target (beam) will allow efficient testing of calculations for $\vec{N} + \vec{d} \rightarrow Nnp$, to address the question of how three-nucleon forces are manifested in scattering. The way in which dedicated experiments can address the questions posed in few-body physics was also discussed by J. van den Brand: examples are the rôles of relativistic corrections and three-body forces.

Round Tables
Besides the numerous parallel sessions, two round-table discussions were held. The first, organised by Yu. Arestov on the RAMPEX experiment, a new spin experiment with 70 GeV/c protons in Protvino, was aimed at uncovering possible measurements (particularly of the single-spin type) that would be suitable for this experiment.
The other, organised by V. Hughes on the gluon spin distribution, had the purpose of concentrating effort towards the search for and measurement of this important quantity at the various experimental facilities, either presently operating or proposed for the future. Many interesting ideas emerged in these discussions and the interested reader is referred to the reports presented in this volume.

Final Words
Spin physics has now definitely come of age, as is more than evident from the wealth of experimental and theoretical results in the field: notably, the accurate determination of structure functions, electro-weak measurements and sophisticated calculations within the framework of perturbative QCD. There are now a number of experiments dedicated to studying spin properties and the SLAC machine may be considered as essentially a polarised facility. On the theoretical side, many phenomenologists traditionally engaged in unpolarised studies have transferred their skills to the spin sector, often finding a much richer structure allowing a deeper insight into the nature of particle interactions. Last but not least, the rôle polarisation has as a precision tool should not be forgotten (e.g., the LEP beam-energy measurement).

Some of the old problems are still with us and many new ones continue to appear; as the older physicist who are still with us know and hopefully the younger ones who are continually appearing will come to appreciate, the field still clearly has a lot more to offer.

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