

Chapter 1

INTRODUCTION

Protons behave like quantum spinning-tops with spin $\frac{1}{2}$ in units of Planck's constant \hbar . This spin is responsible for many fundamental properties of nature including the proton's magnetic moment, the different phases of matter in low temperature physics, the properties of neutron stars and the stability of the known Universe.

One of the main questions in particle and nuclear physics the last 20 years has been: How is the proton's spin built up from its quark and gluon constituents? It is nearly 20 years since the European Muon Collaboration (EMC) published their polarized deep inelastic measurement of the proton's g_1 spin dependent structure function and the flavour-singlet axial-charge $g_A^{(0)}|_{\text{pDIS}}$ [Ashman *et al.* (1988)]. Their results suggested that the quarks' intrinsic spin contributes little of the proton's spin. Relativistic constituent quark models of the proton generally predict that about 60% of the proton's spin should be carried by the spin of its three valence quarks with the rest carried by orbital angular momentum. The most accurate polarization experiments have taught us that the contribution from the spin or helicity of the quarks inside is small, only about 30%, challenging our understanding about the structure of the proton. The challenge to understand the spin structure of the proton has inspired a vast programme of theoretical activity and new experiments at CERN, DESY, JLab, RHIC and SLAC to map out the individual quark and gluon angular momentum contributions to the proton's spin. These experiments are yielding exciting results. *Where are we today? What happens to spin in the transition between current and constituent quarks in low-energy quantum chromodynamics (QCD)?*

The story of the proton's spin dates from the discovery by Dennison (1927) that the proton is a fermion of spin $\frac{1}{2}$. Six years later [Estermann and Stern (1933)] measured the proton's anomalous magnetic moment, $\kappa_p = 1.79$ Bohr magnetons, revealing that the proton is not pointlike and has internal structure. The challenge to understand the structure of the proton had begun!

We now understand the proton as a bound state of three confined valence quarks (spin $\frac{1}{2}$ fermions) interacting through the exchange of spin-one gluons, with the gauge group being colour SU(3) – QCD (quantum chromodynamics, the theory of quarks and gluons). The proton is special because of confinement, dynamical

chiral symmetry breaking and the very strong colour gauge fields at large distances [Thomas and Weise (2001)]. In high-momentum processes the coupling constant or interaction strength for quark-gluon and gluon-gluon interactions is small because of asymptotic freedom. The coupling increases with decreasing momentum or resolution. It becomes so strong that the quarks and gluons are always bound inside nuclear particles like the proton: they are never observed by themselves as free particles. (The restoring confinement force is 10 tonnes regardless of separation.) In low-energy processes the proton behaves like a system of three massive constituent-quark quasi-particles interacting self-consistently with a cloud of virtual pions (light-mass spin-zero particles made out of a quark and an antiquark) and condensates generated through spontaneous breaking of the chiral symmetry between left and right handed quarks. When probed at high resolution the proton looks like three valence “current” quarks plus a sea of quark-antiquark pairs and gluons. The current quarks probed in high-resolution processes are almost massless whereas the constituent quark quasi-particles of low-energy QCD each have a mass about one third of the mass of the proton.

Our present knowledge about the spin structure of the proton at the quark level comes from polarized deep inelastic scattering experiments (pDIS) which use high-energy polarized electrons or muons to probe the structure of a polarized proton and new experiments in semi-inclusive polarized deep inelastic scattering, polarized proton-proton collisions and polarized photoproduction experiments. The spin experiments at CERN, DESY, JLab and SLAC involve firing high-energy charged leptons (electrons or muons) at a polarized proton target. The electron exchanges a deeply-virtual spin-one photon which makes a high resolution probe of the quark-gluon structure of the target. The photon can be absorbed by a spin $\frac{1}{2}$ quark polarized in the opposite direction to the photon but not by one polarized in the same direction as the photon (quarks have no spin $\frac{3}{2}$ state). This allows us to extract information about the spin of the quarks when one controls the polarization of both the beam and the proton target. The RHIC spin experiments involve high-energy polarized proton-proton collisions.

The present excitement and global programme in high-energy spin physics was inspired by an intriguing discovery in polarized deep inelastic scattering. Following pioneering experiments at SLAC [Alguard *et al.* (1976, 1978); Baum *et al.* (1983)], recent experiments in fully inclusive polarized deep inelastic scattering have extended measurements of the nucleon’s g_1 spin dependent structure function (the inclusive form-factor measured in these experiments) over a broad kinematic region where one is sensitive to scattering on the *valence* quarks *plus* the quark-antiquark *sea* fluctuations – see e.g. Windmolders (1999). These experiments have been interpreted to imply that quarks and anti-quarks carry just a small fraction of the proton’s spin ($\sim 30\%$) – about half the prediction of relativistic constituent quark models ($\sim 60\%$). This result has inspired vast experimental and theoretical activity to understand the spin structure of the proton. Before embarking on a detailed

study of the spin structure of the proton it is essential to understand why the small value of this “quark spin content” measured in polarized deep inelastic scattering caused such excitement and why it has so much challenged our understanding of the structure of the proton.

Many elements of subatomic physics and quantum field theory are important in our understanding of the proton spin problem. These include:

- the dispersion relations for polarized photon-nucleon scattering,
- Regge theory and the high-energy behaviour of scattering amplitudes,
- the renormalization of the operators which enter the light-cone operator product expansion description of high energy polarized deep inelastic scattering,
- perturbative QCD: the physics of large transverse momentum plus parton model factorization,
- the non-perturbative and non-local topological properties of gluon gauge fields in QCD and the chiral structure of the QCD θ vacuum,
- the role of gluon dynamics in dynamical chiral symmetry breaking (the large mass of the η and η' mesons and the absence of a flavour-singlet pseudoscalar Goldstone boson in spontaneous chiral symmetry breaking).

In this book we review our present understanding of the proton spin problem and the physics of the new and ongoing programme aimed at resolving the spin-flavour structure of the nucleon.

1.1 Spin and the proton spin problem

Spin is the characteristic property of a particle besides its mass and gauge charges. The two invariants of the Poincare group are

$$\begin{aligned} \mathcal{P}_\mu \mathcal{P}^\mu &= M^2 \\ \mathcal{W}_\mu \mathcal{W}^\mu &= -M^2 s(s+1). \end{aligned} \quad (1.1)$$

Here \mathcal{P} and \mathcal{W} denote the momentum and Pauli-Lubanski spin vectors respectively, M is the particle mass and s denotes its spin. The spin of a particle, whether elementary or composite, determines its equation of motion and its statistics properties. The discovery of spin and its properties are reviewed in Tomonaga (1997) and Martin (2002). Spin $\frac{1}{2}$ particles are governed by the Dirac equation and Fermi-Dirac statistics whereas spin 0 and spin 1 particles are governed by the Klein-Gordon equation and Bose-Einstein statistics.

The proton's spin vector s_μ is measured through the forward matrix element of the axial-vector current

$$2Ms_\mu = \langle p, s | \bar{\psi} \gamma_\mu \gamma_5 \psi | p, s \rangle \quad (1.2)$$

where ψ denotes the proton field operator and M is the proton mass. The quark axial charges

$$2Ms_\mu\Delta q = \langle p, s | \bar{q}\gamma_\mu\gamma_5q | p, s \rangle \quad (1.3)$$

then measure information about the quark “spin content” of the proton. (Here q denotes the quark field operator.) The flavour dependent axial charges Δu , Δd and Δs can be written as linear combinations of the isovector, SU(3) octet and flavour-singlet axial charges

$$\begin{aligned} g_A^{(3)} &= \Delta u - \Delta d \\ g_A^{(8)} &= \Delta u + \Delta d - 2\Delta s \\ g_A^{(0)} &= \Delta u + \Delta d + \Delta s. \end{aligned} \quad (1.4)$$

In semi-classical quark models Δq is interpreted as the amount of spin carried by quarks and antiquarks of flavour q .

In polarized deep inelastic scattering experiments one measures the nucleon’s g_1 spin structure function as a function of the Bjorken variable x , the fraction of the proton’s momentum which carried by quark, antiquark and gluon partons in incoherent photon-parton scattering with the proton boosted to an infinite momentum frame.

Spin sum-rules relate the measured g_1 spin structure function to the quark spin content of the proton. These sum-rules are derived starting from the dispersion relation for polarized photon-nucleon scattering and, for deep inelastic scattering, the light-cone operator product expansion. One finds that the first moment of the g_1 structure function is related to the scale-invariant axial charges of the target nucleon by

$$\begin{aligned} \int_0^1 dx g_1^p(x, Q^2) &= \left(\frac{1}{12}g_A^{(3)} + \frac{1}{36}g_A^{(8)} \right) \left\{ 1 + \sum_{\ell \geq 1} c_{\text{NS}\ell} \alpha_s^\ell(Q) \right\} \\ &+ \frac{1}{9}g_A^{(0)}|_{\text{inv}} \left\{ 1 + \sum_{\ell \geq 1} c_{\text{S}\ell} \alpha_s^\ell(Q) \right\} + \mathcal{O}\left(\frac{1}{Q^2}\right) - \beta_1(Q^2) \frac{Q^2}{4M^2}. \end{aligned} \quad (1.5)$$

Here $g_A^{(3)}$, $g_A^{(8)}$ and $g_A^{(0)}|_{\text{inv}}$ are the isovector, SU(3) octet and scale-invariant flavour-singlet axial charges respectively. The flavour non-singlet $c_{\text{NS}\ell}$ and singlet $c_{\text{S}\ell}$ Wilson coefficients are calculable in ℓ -loop perturbative QCD [Larin *et al.* (1997)]. The term $\beta_1(Q^2) \frac{Q^2}{4M^2}$ represents a possible subtraction constant from the circle at infinity when one closes the contour in the complex plane in the dispersion relation where $\beta_1 \sim 1/Q^2$ for $Q^2 \rightarrow \infty$ for a leading-twist subtraction [Bass (2005)]. If finite, it affects just the first moment sum-rule. The first moment of g_1 plus the subtraction constant, if finite, is equal to the axial-charge contribution. The subtraction constant corresponds to a real term in the spin-dependent part of the forward Compton amplitude.

If one assumes no twist-two subtraction constant ($\beta_1(Q^2) = O(1/Q^4)$) then the axial charge contributions saturate the first moment at leading twist. The isovector axial-charge is measured independently in neutron beta-decays ($g_A^{(3)} = 1.2695 \pm 0.0029$ [Particle Data Group (2004)]) and the octet axial charge is extracted from hyperon beta-decays ($g_A^{(8)} = 0.58 \pm 0.03$). From the first moment of g_1 , polarized deep inelastic scattering experiments have been interpreted to imply a small value for the flavour-singlet axial-charge:

$$g_A^{(0)}|_{\text{pDIS}} \sim 0.15 - 0.35 \quad (1.6)$$

– considerably less than the value of $g_A^{(8)}$. In the naive parton model $g_A^{(0)}|_{\text{pDIS}}$ is interpreted as the fraction of the proton’s spin which is carried by the intrinsic spin of its quark and anti-quark constituents. When combined with the octet axial charge this value corresponds to a negative strange-quark polarization $\Delta s = \frac{1}{3}(g_A^{(0)}|_{\text{pDIS}} - g_A^{(8)})$:

$$\Delta s \sim -0.10 \pm 0.04 \quad (1.7)$$

– that is, polarized in the opposite direction to the spin of the proton. Relativistic quark models generally predict values $g_A^{(0)} \sim 0.6$ with little polarized strangeness in the nucleon.

The small value of $g_A^{(0)}|_{\text{pDIS}}$ suggests the following two questions. *What dynamics suppresses the singlet axial-charge extracted from polarized deep inelastic scattering relative to the OZI prediction $g_A^{(0)} = g_A^{(8)} \sim 0.6$?* Strange quarks or some dynamics related to singlet gluon related dynamics must be at work. *How is the proton’s spin built up from the spin and orbital angular momentum of its constituents?* – viz. one would like to understand the decomposition of the sum-rule for the longitudinal spin structure of the nucleon

$$\frac{1}{2} = \frac{1}{2} \sum_q \Delta q + \Delta g + L_q + L_g \quad (1.8)$$

where L_q and L_g denote the orbital momentum contributions.

The Goldberger-Treiman relation relates the isovector axial charge $g_A^{(3)}$ to the product of the pion decay constant f_π and the pion-nucleon coupling constant $g_{\pi NN}$, viz.

$$2Mg_A^{(3)} = f_\pi g_{\pi NN} \quad (1.9)$$

through spontaneously broken chiral symmetry [Adler and Dashen (1968)]. The Goldberger-Treiman relation leads immediately to the result that the spin structure of the proton is related to the dynamics of chiral symmetry breaking.

What happens to gluonic degrees of freedom? The axial anomaly, a fundamental property of quantum field theory, tells us that the axial-vector current which measures the quark “spin content” of the proton cannot be treated independently of the gluon fields that the quarks live in and that the quark “spin content” is linked to the physics of dynamical axial U(1) symmetry breaking in the flavour-singlet

channel. For each flavour q the gauge invariantly renormalized axial-vector current satisfies the anomalous divergence equation [Adler (1969); Bell and Jackiw (1969)]

$$\partial^\mu (\bar{q}\gamma_\mu\gamma_5q) = 2m\bar{q}i\gamma_5q + \frac{\alpha_s}{4\pi}G_{\mu\nu}\tilde{G}^{\mu\nu}. \quad (1.10)$$

Here m denotes the quark mass and $\frac{\alpha_s}{4\pi}G_{\mu\nu}\tilde{G}^{\mu\nu}$ is the topological charge density. The anomaly is important in the flavour-singlet channel and intrinsic to $g_A^{(0)}$. It cancels in the non-singlet axial-vector currents which define $g_A^{(3)}$ and $g_A^{(8)}$. In the QCD parton model the anomaly corresponds to physics at the maximum transverse momentum squared [Carlitz *et al.* (1988)]. The anomaly contribution also involves non-local structure associated with gluon field topology – see Jaffe and Manohar (1990) and Bass (1998, 2003b). In dynamical axial U(1) symmetry breaking the anomaly and gluon topology are associated with the large masses of the η and η' mesons.

What values should we expect for the Δq ? First, consider the static quark model. The simple SU(6) proton wavefunction

$$\begin{aligned} |p \uparrow\rangle &= \frac{1}{\sqrt{2}}|u \uparrow (ud)_{S=0}\rangle + \frac{1}{\sqrt{18}}|u \uparrow (ud)_{S=1}\rangle - \frac{1}{3}|u \downarrow (ud)_{S=1}\rangle \\ &\quad - \frac{1}{3}|d \uparrow (uu)_{S=1}\rangle + \frac{\sqrt{2}}{3}|d \downarrow (uu)_{S=1}\rangle \end{aligned} \quad (1.11)$$

yields the values $g_A^{(3)} = \frac{5}{3}$ and $g_A^{(8)} = g_A^{(0)} = 1$.

In relativistic quark models one has to take into account the four-component Dirac spinor $\psi = \frac{N}{\sqrt{4\pi}}(\begin{smallmatrix} f \\ i\sigma \cdot \hat{r}g \end{smallmatrix})$ where N is a normalization factor. The lower component of the Dirac spinor is p-wave with intrinsic spin primarily pointing in the opposite direction to the spin of the nucleon. Relativistic effects renormalize the axial charges obtained from SU(6) by the factor $N^2 \int dr r^2 (f^2 - \frac{1}{3}g^2) \sim 0.6$ with a net transfer of angular momentum from intrinsic spin to orbital angular momentum – see e.g. Jaffe and Manohar (1990). $g_A^{(3)} \simeq 1.25$ (in agreement with experiment) and $g_A^{(0)} = g_A^{(8)} \simeq 0.6$. The model prediction $g_A^{(8)} \simeq 0.6$ agrees with the value extracted from hyperon beta-decays [$g_A^{(8)} = 0.58 \pm 0.03$ [Close and Roberts (1993)]] whereas the relativistic quark model prediction for $g_A^{(0)}$ exceeds the measured value of $g_A^{(0)}|_{\text{pDIS}}$ by a factor of 2.

The overall picture of the spin structure of the proton that has emerged from a combination of experiment and theoretical QCD studies can be summarized in the following key observations:

First, the isovector Bjorken (1966, 1970) spin sum-rule relating the first moment of the isovector combination $g_1^{(p-n)} = g_1^p - g_1^n$ to the nucleon's isovector axial-charge $g_A^{(3)}$ has been successfully tested to better than 10% accuracy. Further, in the measured “small x ” region $0.02 < x < 0.1$ the isovector spin structure exhibits a valence like rising behaviour $\sim x^{-0.5}$ in an x range where one would, a priori, not necessarily expect quark model results to apply. Constituent quark

model predictions work remarkably well for the isovector part of the nucleon's g_1 spin structure function at deep inelastic Q^2 [Bass (1999)].

Second, there has been considerable theoretical effort to understand the flavour-singlet axial-charge in QCD and the small value of $g_A^{(0)}|_{\text{pDIS}}$. QCD theoretical analysis leads to the formula

$$g_A^{(0)} = \left(\sum_q \Delta q - 3 \frac{\alpha_s}{2\pi} \Delta g \right)_{\text{partons}} + \mathcal{C}_\infty. \quad (1.12)$$

Here $\Delta g_{\text{partons}}$ is the amount of spin carried by polarized gluon partons in the polarized proton and $\Delta q_{\text{partons}}$ measures the spin carried by quarks and antiquarks carrying “soft” transverse momentum $k_t^2 \sim P^2, m^2$ where P is a typical gluon virtuality and m is the light quark mass [Efremov and Teryaev (1988); Altarelli and Ross (1988)]. Since $\Delta g \sim 1/\alpha_s$ under QCD evolution, the polarized gluon term $[-\frac{\alpha_s}{2\pi} \Delta g]$ in Eq. (1.12) scales as $Q^2 \rightarrow \infty$ [Efremov and Teryaev (1988); Altarelli and Ross (1988)]. The polarized gluon term is associated with events in polarized deep inelastic scattering where the hard photon strikes a quark or antiquark generated from photon-gluon fusion and carrying $k_t^2 \sim Q^2$ [Carlitz *et al.* (1988)]. \mathcal{C}_∞ denotes a potential non-perturbative gluon topological contribution [Bass (1998)] which is associated with the possible subtraction constant in the dispersion relation for g_1 [Bass (2005)]. It affects only the first moment and has support only at Bjorken x equal to zero so that it cannot be directly measured in polarized deep inelastic scattering.

The topological term \mathcal{C}_∞ may be identified with a leading twist “subtraction at infinity” in the dispersion relation for g_1 . It probes the role of gluon topology in dynamical axial U(1) symmetry breaking in the transition from current to constituent quarks in low energy QCD. If \mathcal{C}_∞ is finite it would mean that $\lim_{\epsilon \rightarrow 0} \int_\epsilon^1 dx g_1$ will measure the difference of the singlet axial-charge and the subtraction constant; that is polarized deep inelastic scattering measures the combination $g_A^{(0)}|_{\text{pDIS}} = g_A^{(0)} - \mathcal{C}_\infty$. The deep inelastic measurement of $g_A^{(0)}$, Eq. (1.6), is not necessarily inconsistent with the constituent quark model prediction 0.6 if a substantial fraction of the spin of the constituent quark is associated with gluon topology in the transition from constituent to current quarks (measured in polarized deep inelastic scattering).

Possible explanations for the small value of $g_A^{(0)}$ extracted from the polarized deep inelastic experiments include screening from positive gluon polarization, negative strangeness polarization in the nucleon, a subtraction at infinity in the dispersion relation for g_1 associated with non-perturbative gluon topology, and connections to axial U(1) dynamics.

Why is the measured quark spin contribution so small compared to quark model predictions? Is the “missing spin” a valence quark or a sea effect? Are the quark-antiquark sea excitations polarized in the opposite direction to the proton's spin (thus cancelling some of the spin)? The spin of the gluons which bind the proton can screen the spin of the quarks measured in high-energy experiments through

Eq. (1.12). (Here $\alpha_s \sim 0.3$ is the QCD coupling at the scale of the present experiments and Δg is the gluon polarization). How large is the gluon polarization? The QCD vacuum is a quantum superposition of an infinite number of states characterized by non-local topological properties of QCD and non-trivial spin structure. When one puts a valence quark in this vacuum as a “source”, the spin of the constituent quark can become delocalized so that the total spin becomes a property of the proton rather than the sum over localized current quark contributions probed in high energy experiments. How big is this effect?

A direct measurement of the strange-quark axial-charge, independent of the analysis of polarized deep inelastic scattering data and any possible “subtraction at infinity” correction, could be made using neutrino proton elastic scattering through the axial coupling of the Z^0 gauge boson. Comparing the values of Δs extracted from high-energy polarized deep inelastic scattering and low-energy neutrino-proton elastic scattering will provide vital information about the QCD structure of the proton.

On the theoretical side, when assessing models which attempt to explain the proton’s spin structure it is important to look at the transverse momentum dependence of the proposed dynamics plus the model predictions for the shape of the spin structure functions as a function of Bjorken x in addition to the first moment and the nucleon’s axial charges $g_A^{(3)}$, $g_A^{(8)}$ and $g_A^{(0)}$.

There is presently a vigorous programme to disentangle the different contributions. Key experiments involve semi-inclusive polarized deep inelastic scattering (COMPASS and HERMES) and polarized proton-proton collisions at the world’s first polarized proton-proton collider RHIC (PHENIX and STAR), and future polarized electron-proton collider studies. Experiments at Jefferson Laboratory are probing the spin properties of valence quarks in kinematics where they are sensitive to the confinement process.

Measurements by the COMPASS Collaboration at CERN and PHENIX and STAR experiments at RHIC suggest that the gluon polarization is much too small to resolve the difference between the quark model prediction $\sim 60\%$ for the quark spin contribution and the measured value $\sim 30\%$ through the anomaly mechanism although it may still make an important contribution to the net spin of the proton [Bass and Aidala (2006); Mallot (2006)]. The COMPASS and RHIC experiments use different processes to access the gluon polarization. The COMPASS measurements are extracted from the production of charm-particles and charged-particles with large transverse-momentum in polarized muon-nucleon collisions. The RHIC measurements are extracted from high-energy particle production in polarized proton-proton collisions. Measurements of the sea polarization by the HERMES experiment (DESY) suggest that this is also small, too small to resolve the spin puzzle and that the 30% quark spin contribution is approximately saturated by valence quark contributions [Airapetian *et al.* (2004)]. Independent measurements of the valence and sea quark contributions are being made by COMPASS.

Further interesting information about the structure of the proton are coming from the study of “transversity” spin distributions [Barone *et al.* (2002)]. Working in an infinite momentum frame, these observables measure the distribution of spin polarized transverse to the momentum of the proton in a transversely polarized proton. Since rotations and Euclidean boosts commute and a series of boosts can convert a longitudinally polarized nucleon into a transversely polarized nucleon at infinite momentum, it follows that the difference between the transversity and helicity distributions reflects the relativistic character of quark motion in the nucleon. Furthermore, the transversity spin distribution of the nucleon is charge-parity odd ($C = -1$) and therefore valence like (gluons decouple from its QCD evolution equation in contrast to the evolution equation for flavour-singlet quark distribution appearing in g_1) making a comparison of the different spin dependent distributions most interesting. Studies of transversity sensitive observables in lepton nucleon and polarized proton-proton scattering are being performed by the HERMES [Airapetian *et al.* (2005b)], COMPASS [Ageev *et al.* (2007)] and RHIC [Adams *et al.* (2004)] experiments.

One would also like to measure the parton orbital angular momentum contributions to the proton’s spin. Exclusive measurements of deeply virtual Compton scattering and single meson production at large Q^2 offer a possible route to the quark and gluon angular momentum contributions through the physics and formalism of generalized parton distributions [Ji (1998); Goeke *et al.* (2001); Diehl (2003)]. A vigorous programme to study these reactions is being designed and investigated at several major world laboratories.

Spin measurements have a bright future, continue to surprise and to challenge our understanding about the structure of the proton and fundamental aspects of quark dynamics. Much exciting progress has been made. The next years promise to be equally exciting.

1.2 Outline

The book is organized as follows. In the first part (Chapters 2-8) we review the present status of the proton spin problem focussing on the present experimental situation for tests of polarized deep inelastic spin sum-rules and the theoretical understanding of $g_A^{(0)}$. In the second part (Chapters 9-15) we give an overview of the present global programme aimed at disentangling the spin-flavour structure of the proton and the exciting prospects for the new generation of experiments aimed at resolving the proton’s internal spin structure. In Chapters 2-4 we give an overview of the derivation of the spin sum-rules for polarized photon-nucleon scattering, detailing the assumptions that are made at each step. Here we explain how these sum rules could be affected by potential subtraction constants (subtractions at infinity) in the dispersion relations for the spin dependent part of the forward Compton amplitude. We next give a brief review of the partonic (Chapter 3) and possible fixed

pole (Chapter 5) contributions to deep inelastic scattering. Fixed poles are well known to play a vital role in the Adler sum-rule for W-boson nucleon scattering [Adler (1966)] and the Schwinger term sum-rule for the longitudinal structure function measured in unpolarized deep inelastic ep scattering [Broadhurst *et al.* (1973)]. We explain how fixed poles could, in principle, affect the sum-rules for the first moments of the g_1 and g_2 spin structure functions. For example, a subtraction constant correction to the Ellis-Jaffe sum rule for the first moment of the nucleon's g_1 spin dependent structure function would follow if there is a constant real term in the spin dependent part of the deeply virtual forward Compton scattering amplitude. Chapter 6 discusses the QCD axial anomaly and its possible role in understanding the first moment of g_1 . The relationship between the spin structure of the proton and chiral symmetry is outlined in Chapter 7. This first part of the paper concludes with an overview in Chapter 8 of the different possible explanations of the small value of $g_A^{(0)}$ that have been proposed in the literature, how they relate to QCD, and possible future experimental tests which could help clarify the key issues. We next focus on the new programme to disentangle the proton's spin-flavour structure and the Bjorken x dependence of the separate valence, sea and gluonic contributions (Chapters 9-12), the theory and experimental investigation of transversity observables (Chapter 13), quark orbital angular momentum and exclusive reactions (Chapter 14) and the g_1 spin structure function of the polarized photon (Chapter 15). A summary of key issues and challenging questions for the next generation of experiments is given in Chapter 16.

Complementary review articles on the spin structure of the proton, each with a different emphasis, are given in Anselmino *et al.* (1995), Cheng (1996), Shore (1998b), Lampe and Reya (2000), Fillipone and Ji (2001), Jaffe (2001), Barone *et al.* (2002), Stoesslein (2002), Bass (2005) and Bass and Aidala (2006).