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AN OVERVIEW OF SPIN PHYSICS*

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ABSTRACT

Spin physics is playing an increasingly important role in high energy experiments and theory. This review looks at selected topics in high energy spin physics that were discussed at the 9th International Symposium on High Energy Spin Physics at Bonn in September 1990.

INTRODUCTION

Spin physics is a very broad subject that plays a role to some degree in almost all areas of particle and nuclear physics. Spin is often regarded as an unwanted nuisance and a complication in progress toward a better understanding of the fundamental laws. This is particularly so when it comes to new experimental facilities where spin has been characterized as the poor stepsister to energy and luminosity. Designers of new accelerators are sufficiently burdened with the complicated needs of the facility that they are reluctant to accept the additional constraints and complications that would be required to accelerate polarized beams successfully. Arguments are heard that minimize the need for polarized beams. Projects move ahead without the capabilities for accelerating polarized beams because money and time are limited, and the technical uncertainties connected with polarization do not allow for such possibilities to be incorporated at the beginning. In spite of these problems, spin shows an increasing degree of importance in many areas of particle physics. This growing importance is occurring through strong support in areas of technology connected with spin. Technology is providing new tools which make new experiments in spin physics possible.

In the following review, the subject of spin is organized into three basic categories: intrinsic spin, composite spin, and spin technology. In the first, the historical development of our concept of spin is reviewed, the present day role of spin in the standard model is emphasized, and current activities that relate to intrinsic spin are discussed. In the second part, composite spin, baryons are discussed at some length. Composite spin involves a discussion of magnetic moments, polarization of baryons in inclusive scattering at high energies, spin structure from deep inelastic scattering, and other topics. Finally, spin technology is mentioned. It represents a broad category of topics, too many to discuss in detail here. Spin technology touches on many fields in physics, from condensed matter physics, to atomic physics, and to future accelerator applications. Advances in spin technology feed the experimental world where advances inour understanding and the ability to ask experimental questions are occurring. The strong rate of progress in experiments is riding on the back of the progress in technology. The full subject of spin research is beyond the scope of this talk. In this review, highlights of recent developments will be mentioned.

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Historically spin has been an essential part of understanding of the physical laws of nature. The classical laws of mechanics recognized this. The second law of Kepler, in 1609, was a statement of conservation of angular momentum in the motion of planets. In the 1920's, the classical laws failed to describe properly the behavior of atoms, and quantum mechanics was developed to explain the atomic and subatomic world. In 1925 the Pauli exclusion principle was established, leading to a connection between spin and statistics.[1] Also at that time in 1925, Uhlenbeck and Goudsmit first hypothesized that the electron carried a new degree of complexity, spin.[2] At first the concept was not well received. Shortly thereafter, in 1926, Thomas provided a relativistic calculation of the behavior of electrons with spin in atoms.[3] This calculation resolved a factor-of-two discrepancy in the spin-orbit coupling parameters in atoms. The concept of spin as an intrinsic property of the electron was thereafter widely accepted. In 1928 Dirac, in an elegant synthesis of concepts, developed the Dirac equation, which for a free spin-1/2 particle is described by[4]

$$(i\hbar\not\nabla - mc)\Psi = 0.$$

This is a relativistically covariant equation with solutions which are 4-component spinors. The interpretation of these solutions required positive and negative energy states with spin components ±1/2 each. Anti-particle states were required and therefore were a prediction of the Dirac formulation. When the electromagnetic field was included, the Dirac theory became the basis for QED, quantum electrodynamics. Renormalizability and the smallness of the coupling α led to a calculable theory that has had unsurpassed successes in experiment and theory. The experiments which look at the spin motion are the best example of the precision comparison between experiment and theory.

Today, in the 1990's, our modern view of the substructure of matter is embodied in the Standard Model consisting of three generations, or families, of quarks and leptons, plus five vector bosons which mediate the forces between them.

$$\begin{bmatrix} u \\ d \\ e \\ \nu_e \end{bmatrix} \begin{bmatrix} c \\ s \\ \mu \\ \nu_\mu \end{bmatrix} \begin{bmatrix} (t) \\ b \\ \tau \\ \nu_\tau \end{bmatrix} \text{ and } [\gamma, g, W^\pm, Z^0] \quad .$$

Data from LEP says that the width of the Z° boson is consistent with three families, and rule out the possibility of light neutrinos from a fourth generation.[5] Within each generation there are two quarks, each in three colors, and a charged and neutral lepton. These objects are all spin-1/2 fermions. What defines "familiness" is not known. For example, what prevents $\mu \rightarrow e + \gamma$? The branching ratio for this is $< 5 \times 10^{-11}$. We explain this as "lepton conservation," but the rule we invoke here is not an explanation. Something yet unknown about these objects prevents this transition. Why should the fundamental constituents be spin-1/2 objects, and not something else such as spin-0 objects? These deeper issues are not yet understood. The proliferation of these fundamental particles may hint at a deeper level of matter. Compositeness is one hope for finding a deeper explanation than we have today.

Of the fundamental particles, the electron and muon hold a special place. These objects can be confined in "bottles" and held for detailed studies. That is not possible for quarks, which apparently are confined, so we can never find them alone. The neutrinos are free, but being uncharged and weakly interacting cannot be held. The tau lepton decays too rapidly for precision experimental use. Only the electron and muon allow us to hold them and to study them closely. The g-2 measurements on these objects have been enormously important to our understanding.

Dynamical structure shows up as an anomalous magnetic moment due to charged constituents within, circulating about the center. The circulating constituents generate circulating currents, and therefore lead to a magnetic dipole component due to this dynamical structure. In 1980 Brodsky and Drell discussed a model of the electron in which constituents were hypothesized, a charged fermion and a neutral boson, coupled by some force.[6] They argued that the composite structure leads to an added component in the magnetic moment

$$\delta a = m_e/m^* = m_e R_e$$

where m_e is the electron mass and m^* is an effective mass of the composite scale. The corresponding radius of the object is R_e.

From Bhabha scattering at high energies, deviations from pure point-like QED would be evidence for compositeness. Experimental measurements place a limit $R_e < 10^{-16}$ cm approximately. The electron g-2 measurements place independent limits on compositeness. The experimental value[7]

$$a_e^{\text{exp}} = \left[\frac{g-2}{2}\right]_e = .001\ 159\ 652\ 188(4)$$

and the theoretical value[8]

$$a_e^{\text{theory}} = \left[\frac{g-2}{2}\right]_e = .001\ 159\ 652\ 140(28)$$

agree to ≈ 40 parts per billion. The difference represents the possible contribution from a composite structure. The equivalent effective radius is $R_e < 2 \times 10^{-21}$ cm, based on the relation $\delta a = m_e R_e$ from Brodsky and Drell. The effective mass of the composite scale is $m^* > 1000$ TeV! The extremely precise low energy experiment yields a truly remarkable high energy limit.

These extremely restrictive limits are perhaps unduly pessimistic if you are a believer in compositeness. Brodsky and Drell suggest that models can be constructed which avoid such extreme limits. Chiral invariant couplings remove the linear dependence on mass, leaving $\delta a = (m_e/m^*)^2$, so that $m^* > 1$ TeV. This is the value used to characterize the sensitivity of the electron g-2 data today.

The muon g-2 situation is similar to that of the electron.[9,10]

$$a_\mu^{\text{exp}} = .001\ 165\ 924(8.3)$$

and

$$a_\mu^{\text{theory}} = .001\ 165\ 919(1.7)$$

The sensitivity to composite structure is $m^* > 1$ TeV, like the electron. The precision of the theory is not as high as for the electron, but the heavier mass of the muon makes this comparison as sensitive.

Brodsky and Drell argue that any successful theory of composite structure must explain adequately the facts that δa and δm (corrections to the mass) nearly vanish.

In summary, the extremely precise g-2 measurements show no evidence for composite structure. The spin of these objects appears to us to still be an intrinsic property.

One active planned experiment, the Brookhaven experiment AGS 821, seeks to improve the accuracy for the muon g-2 by a factor of 20 over existing data. This experiment is in preparation today. Its objective is to reach mass scales of 2 to 3 TeV, a mass scale comparable to what can be achieved only in the future by SSC. This is a fundamentally important piece of work which bears on the issues of spin and the structure of these basic bits of matter, the leptons.

The origins of spin is still a deep mystery. It may be beyond the reach of experimental tools today to shed light on the nature of intrinsic spin. It is surely as interesting and as important to our understanding of the nature of matter as is, for example, the questions of the origin of mass. The issues of the origin of mass, and the search for particles responsible, motivate in part our push to higher energy accelerators. Hopefully these future tools can shed light on the nature of spin as well.

COMPOSITE SPIN

In this part, an enormous body of work on composite objects, the baryons, will be summarized. There appear to be several important common themes that tie the following subjects together. They include (i) the study of spin-dependent effects in baryons leads quickly and naturally to issues within QCD; (ii) QCD has problems with the large spin asymmetries seen in high energy scattering processes. Perturbative QCD lacks the mechanisms to generate these asymmetries, and the full QCD theory presently offers no conceptual path to an explanation of these data. On the experimental side, the spin asymmetries are seen in a wide variety of scattering processes. The asymmetries seem to grow stronger as energies and momentum transfers increase, contrary to QCD concepts. No progress on this impasse has occurred for a number of years; and (iii) strangeness seems to play an important role, even in the simplest of the baryons, the proton.

Magnetic Moments

Magnetic moments of the baryons has been a favorite subject of quark model advocates for many years. The experimental situation has been clean and active. Direct production of hyperons at high energies has been quite fruitful in recent times. Within the past year, we have seen a measurement of the magnetic moment of the Ω^- reported.[11] With the observation of sizeable transverse polarizations in high energy high p_t production of hyperons, measurement of magnetic moments by brute force precession in magnetic fields has been possible, and in fact the source of most of the information. Additional data from other techniques, fine splitting in exotic atoms, and for the Σ°, use of the transition magnetic moment from the $\Sigma^\circ \rightarrow \Lambda\gamma$ decay process, exist. We now have measurements for the full baryon octet, plus the Ω^- from the baryon decouplet. Reviews and summaries of the analysis of magnetic moments exist.[12] This subject has been a cottage industry of its own, because of the interest in baryon structure, the success of the quark-parton picture, and the high quality of the data.

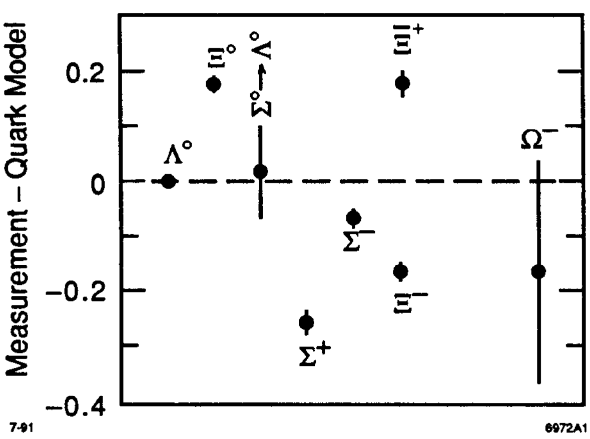

Fig. 1. Deviations of the magnetic moments of hyperons from a naive quark model estimate (see Ref. 12) are shown. In this version, magnetic moments of the p, n and Λ° are inputs to the model.

An example of one analysis is illustrated here.[12] The input to this model assumes the static quark model with SU(6) wave functions for the baryons. The valence quarks u, d, and s are assigned corresponding effective magnetic moments μ_u, μ_d, and μ_s. The values for μ_u, μ_d, and μ_s can be adjusted. In this particular analysis, the precise μ_p, μ_n, and μ_Λ are used as input to determine μ_u, μ_d, and μ_s. In other analyses, these parameters can be set by other means. Figure 1 shows the deviations in nuclear magnetons for each baryon measured. Deviations of ±0.2 nm are seen, with the experimental errors substantially smaller. It is clear that the major part of the baryon magnetic moments are well described by the static quark model. It is also clear that discrepancies exist at the 0.2 nm level. Attempts to improve the simple picture by adding corrections do not substantially improve the picture. These attempts include estimates of contributions from meson currents, gluon currents, relativistic corrections, admixtures of orbital configurations in the wave functions, mass effects, and polarization of the sea quarks. This latter point, the polarization of the sea quarks, will be revisited later in this review.

Future experiments may attempt to measure magnetic moments for charmed baryons. Techniques using bent crystals as a means of precessing these short-lived particles have been suggested. The techniques today sound problematic, but advances in techniques may occur which make these measurements possible.

Hyperon Polarization

In inclusive hyperon production from high energy proton beams interacting in nuclear material, the outgoing hyperon is observed to be polarized. Parity conservation in the process prohibits spin components in the production plane, but allow for the component perpendicular to the plane to exist. Nature seems to take full advantage of the window of opportunity—the polarization out of the plane is often large.

Using the weak decays of the hyperon to analyze the hyperon polarization, the transverse polarization has been studied rather extensively in a series of experiments.[13] The polarization grows approximately linearly in momentum and in p_t up to values as large as ± 0.3 for the highest p_t data. The data show no evidence of decreasing polarization as the beam energy, momentum, or p_t increase.

Rules which "explain" the features of these data have been concocted, since no theory exists which attempts to explain these results. The rules are paraphrased as: (i) in the hyperon production process, one or two valence quarks come from the incoming projectile; if not the polarization is zero (for example for the Ω^-); (ii) The hyperon picks up a strange quark from the target sea. This strange quark becomes negatively polarized (somehow); and (iii) the hyperon consists of valence quarks in an SU(6) wave function.

With these rules, the systematics of the data are mostly explained. The Σ^+ and the Σ^- are polarized in a positive sense. The Λ°, Ξ^+, and Ξ^- are polarized in a negative sense. Anti-hyperons are unpolarized, as is the Ω^-.

These rules were suggested solely to provide a systematic picture. The recent measurement of the polarization of the $\Omega^- \approx 0$ was a "prediction" from these rules.

Quite recently, measurements at Fermilab of the polarization of the anti-Ξ^- have been reported.[14] The rules predicted zero polarization, but the data clearly exhibit a nonzero value near -10% with small errors. The apparent conclusion is that these simple rules do not suffice in all cases. The data are quite recent, so with some thought modifications to the rules may be possible. Meanwhile the systematics of the hyperon polarization remain puzzling.

Having an ad hoc set of rules that either work or do not work is not very relevant. The real issue of some concern does not relate to these rules. The real issue concerns QCD and how such nonzero polarization can arise. It is quite clear that these transverse polarizations are large and not going away as energies and momenta increase. Perturbative QCD has no mechanism for generating these polarizations. In a massless QCD theory, helicity of the quarks is conserved at the quark-quark-gluon vertex. Multiple gluon emissions or absorptions preserve helicity. It is not possible in perturbative QCD mechanisms for an unpolarized incoming quark to become polarized through gluon exchanges. Perturbative QCD is simply incapable of explaining these processes.

This fact has been pointed out many times. Could these transverse polarizations be related to the strange quark in the hyperons? It is interesting to look at other processes which do not directly involve strange quarks. High quality data exist for p-p elastic scattering.[15] These data include single spin transverse asymmetries (A_n) and double spin transverse asymmetries (A_{nn}). In both cases we see unambiguous large nonzero asymmetries. There have been suggestions that the elastic p-p data, taken at 90 degrees in the center-of-mass system, reflect a particle identity effect. This however, does not seem to be the explanation, because these effects are also seen away from 90 degrees. Again we are apparently seeing nonperturbative QCD effects in high energy hadron processes. Going beyond elastic p-p scattering, we can find transverse asymmetries in inclusive π^0 production from both p and $\bar{\text{p}}$ polarized beams. These asymmetries show no sign of going away at higher energies. Perturbative QCD simply cannot be considered appropriate to this class of experimental phenomena, namely single and double spin asymmetries.

In defense of PQCD, the objects under study are complicated and composite. Gluons couple to quarks and to gluons. The quarks apparently suffer from "confinement" which physically must be a strong force. QCD does not explain this. Confinement, if valid, represents forces beyond the perturbative level. The multi-body problem is likely to be difficult and intractable in any case.

Must we discard the underlying QCD theory? Certainly not. The successes are too important to ignore. Gluons exist, as evidence from e^+e^- annihilation point to. A color degree-of-freedom exists. The strong coupling is seen to run. The evolution of deep inelastic structure functions of the nucleon clearly point to a QCD-type substructure. Phenomenological success of the Lund-type generators represent a practical benefit resulting from QCD-inspired models. These are major successes for QCD. But QCD has failed to give us guidance in certain areas, most notably those processes discussed above involving spin. This failure on the part of QCD to provide us with conceptual insights is unfortunate.

Progress in this area may come from experiments with spin. That is the subject of the next section.

The Spin Structure of the Nucleon

In the recent past, substantial progress has been made in understanding the structure of the nucleon. Experiments which probe the spin substructure in deep-inelastic scattering have led to some surprises. Experiments planned for the near future will help shed more light on the subject. The experimental data from μp and ep deep inelastic scattering using polarized beams and polarized targets shows rather substantial quark polarization ina polarized proton. Figure 2 shows the asymmetry A_1^p from three experiments, E80, E130 at SLAC, and the EMC experiment at CERN.[16] The physics asymmetry A_1^p is defined as

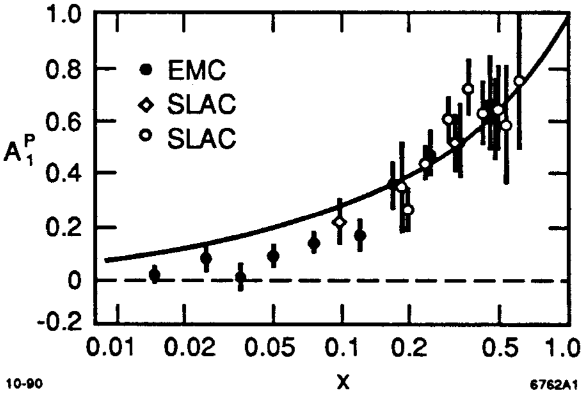

Fig. 2. The physics asymmetry $A_1^p(x)$ from three experiments.

$$A_1^p = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

where $\sigma_{1/2}(\sigma_{3/2})$ refers to the anti-parallel (parallel) alignment of longitudinal spins of the virtual photon and target. The physics asymmetry is related to the experimental asymmetry and to the raw asymmetries through factors involving kinematics, beam polarization, and target polarization. The physics asymmetry is related to the spin-dependent structure function

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

where small corrections arising from other terms are neglected here. This quantity is the integrand for the Ellis-Jaffe sum rule,[17] given by

$$\int_0^1 g_1^p(x)\,dx = \frac{1}{12}\left|\frac{g_A}{g_V}\right|\left[1+\frac{5}{3}\frac{3\mathrm{F/D}-1}{\mathrm{F/D}+1}\right] + O(\alpha_s) = 0.189 \pm 0.005$$

The Ellis-Jaffe sum rule is based on quark light-cone algebra and assumptions involving SU(3) invariance. The quark light-cone algebra is today regarded as valid. The assumptions concerning SU(3), and particularly the assumption that strange quarks within a proton do not contribute to spin, are questioned. The analysis of the experimental data show a smooth extrapolation to 0.114±0.012±0.026, as indicated in Figure 3. Based on these measurements and the evaluation of the Ellis-Jaffe sum rule, the EMC Collaboration extracted the contribution to the proton for each quark type $\Delta u = 0.373 \pm 0.019 \pm 0.039$, $\Delta d = -0.254 \pm 0.019 \pm 0.039$, and $\Delta s = -0.113 \pm 0.019 \pm 0.039$, where $\Delta q = \int_0^1 (q^{\uparrow} - q^{\downarrow} + \bar{q}^{\uparrow} - \bar{q}^{\downarrow})dx$. The net quark spin $\Delta u + \Delta d + \Delta s = -0.006 \pm 0.058 \pm 0.117$ compared to the expectation of 1/2 for a polarized proton. The net quark spin is *zero*?! Furthermore, the strange quarks are negatively polarized. And finally, if the spin is not carried by the quarks, then where? With orbiting constituents or gluons? The questions certainly exist now, but upcoming experiments will soon be able to address them.

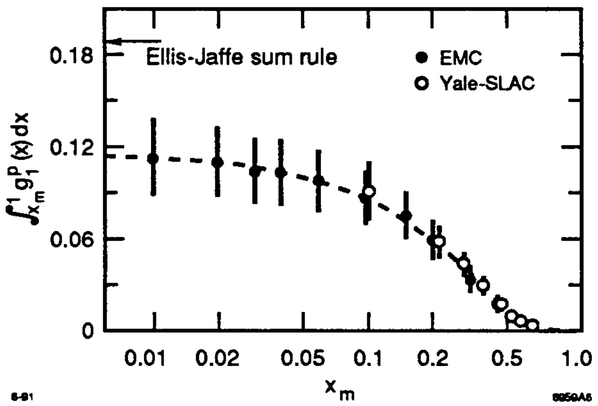

Fig. 3. The integral of $g_1^p(x)$ versus the lower limit x_m from Ref. 16. The errors shown are combined statistical and systematic errors.

Meanwhile, a cottage industry of "crisis avoidance" has sprung up around the "spin crisis" as the situation has been dubbed. Critical review of the several assumptions and analyses underlying these surprising conclusions has occurred. In each case, modest to serious controversy circulates around these issues. The F/D parameter in the Ellis-Jaffe sum rule is the ratio of the SU(3) axial charges obtained from hyperon decays. The value most often quoted[18] is

F/D $=-0.631\pm0.018$. A recent re-analysis of the data, with the spin crisis motivating the re-analysis, has been reported.[19] The set values for F/D coming from various model assumptions ranges as low as 0.55 and as high as 0.71. The best value agrees well with previous work. Within this range, the Ellis-Jaffe sum rule still falls well above the experimental measurement published by the EMC Collaboration. Apparently reasonable F/D values do not allow for a resolution of the spin crisis.

The experimenters have been careful to look at the $Q^2 \rightarrow \infty$ limit. The $O(\alpha)$ corrections are QCD corrections to account for finite values of Q^2. The inelastic scattering data from ep and μp show independence in Q^2 down to values as low a 1 $(\mathrm{GeV/c})^2$. This is true for the unpolarized structure functions. For the spin-dependent structure functions, the asymmetries are shown to be Q^2 independent for the data[16] shown in Figure 2. Care in interpreting these data is suggested. The structure function g_1^p is related to A_1^p through other terms, and those may introduce a Q^2 dependence not seen in A_1^p. Furthermore, the data on A_1^p are not very precise. Future experiments should be careful to look at the Q^2-dependence, particularly in the low x region which will be sensitive to this issue.

Extrapolation of the measured integral to $x = 0$ is important. Figure 3 shows the data that exist. The low x region is particularly important to the integral. High energy beams are required for low x because the data require high Q^2 as well. This region will be mapped best by the planned experiments at CERN, using the high energy muon beam available there. At the present, there is no evidence that the low x region will provide sufficient contribution to the integral to fulfill the Ellis-Jaffe sum rule.

Contributions to the asymmetry A_1^p can potentially arise from the second spin structure function g_2. This structure function, like g_1, can have effects at low x. The possibility that g_2 may be mixed in at low x is unlikely in the present data, because of the high beam energies and high Q^2 values involved. The issues were discussed in 1988 at the Theory Workshop as part of the Minneapolis High Energy Spin Symposium. The workshop conclusion stated that problems with the sum rule were unlikely to stem from the g_2 terms. Future experiments are likely to make measurements of g_2 to verify these conclusions.

QCD corrections have been a topic of considerable discussion. Jaffe in 1987,[20] Altarelli and Ross in 1988,[21] and others point to the triangle anomaly which can make contributions to the Δu, Δd, and Δs terms through gluonic processes. Such anomalies arise in processes involving axial current matrix elements. Analysis of the triangle diagrams show that quark spin terms Δq should be modified by $\Delta q \rightarrow \Delta q - \alpha/2\pi\Delta G$, where ΔG is a term arising from polarized gluons in the nucleon. It is suggested that perhaps ΔG is large, and therefore suppresses the sum $\Delta u + \Delta d + \Delta s$ to a value that is small. Other authors argue that correct treatment of the triangle anomaly leaves the contribution of gluonic spin negligible. These issues are today still controversial and remain to be resolved. At present, the general attitude is that gluonic corrections do not substantially modify our conclusion that $\Delta u + \Delta d + \Delta s = 0.0$ to 0.2. Given the present status, namely that no obvious problems with the data exist, and that theoretical issues do not substantially modify our understanding, then we conclude that the Ellis-Jaffe sum rule is violated substantially, and our simple picture of the nucleon must be changed. A likely explanation is that the strange quarks are polarized (negative in a polarized proton). Spin must be carried by orbiting components and/or polarized gluons. These modified ideas of the proton structure will be tested more extensively in the near future as the experimental data improves.

Where do we go from here? Upcoming experiments at CERN, DESY, and SLAC are being planned. Four projects are now active. At CERN, the SMC Collaboration is currently in a planned run with a polarized deuterium target. SMC plans to take data down to $x = .005$ for both the neutron and the proton. At SLAC, the experiment E142 is in preparation. That experiment will use a ^{3}He target to measure the spin structure of the neutron. It is scheduled to run in the latter half of 1992. Future experiments at DESY (HERMES) and CERN (HELP) are in various phases of proposal and approval. These experiments have their own unique capabilities, with separate and independent sources of systematic errors. The collection of upcoming experiments should provide ample data to unravel the questions of spin structure of the nucleon.

The Bjorken sum rule and the Ellis-Jaffe sum rules are closely related. The Bjorken sum rule, simply stated, is the difference of the Ellis-Jaffe proton and neutron sum rules. Bjorken derived this sum rule in 1966, based on quark light-cone algebra and isospin symmetry. The derivation assumes that the electromagnetic current of the hadronic material is expressed in the $Q^2 \rightarrow \infty$ limit by interaction with quarks. By taking a proton-neutron difference, the sum rule avoids the model dependent assumptions found in the Ellis-Jaffe sum rules. The original derivation in 1966 was characterized by Bjorken as "worthless" because the experimental requirements (polarized neutrons) looked impractical to him.[22] Theoretical interest in a developing field, QCD, and experimental progress in polarized targets led him to revisit the subject in 1969 with considerable enthusiasm.[23] This enthusiasm was reinforced by Feynman.[24] Today the Bjorken sum rule is regarded as a test of QCD. The derivation assumes that the electromagnetic interaction of the nucleon is given by interactions at short distances with quarks. It requires that the equal time commutation relation of the currents be valid. Failure of the sum rule would possibly uproot the foundations of QCD.

Nobody today believes that the Bjorken sum rule will fail. The underpinnings of QCD are too solid. We have strong indications from $e^+e^- \rightarrow$ hadrons, for example, that the basic structure of the electromagnetic currents of hadrons is correct. Nevertheless, it is nearly unthinkable that such a fundamental relation derived in 1966 remains untested today. This situation is about to be corrected. In the next several years, proposed experiments should provide a test of the Bjorken sum rule to better than 10%.

Magnetic Moments again

Before leaving the subject of composite spin, there remains one issue which should be mentioned. We have seen that the static quark model of the baryons is largely successful in describing hyperon magnetic moments, with the magnetic moments of the baryons being the sum of the magnetic moments of the valence quarks. We have seen that the EMC results suggest that the spin of the proton is not carried by the quarks. Are these conclusions not incompatible? This question has recently been studied.[25,26] In the studies, the relation between magnetic moments and the Δq's is examined more closely. These papers conclude that $\Delta u + \Delta d + \Delta s$ is small and that the proton spin does not come from the quark spin alone. Inclusion of a small negative Δs arising from the sea quarks is suggested and is compatible with models of hyperon magnetic moments. Inclusion of the Δs term is shown to improve modestly the naive quark model fits to the magnetic moments. Discrepancies of $\leq \pm 0.1$ nm in the magnetic moments still remain. However no contradiction with the EMC results is seen.

SPIN TECHNOLOGY

Spin technology is a subject too large for this review. It touches all fields of experimental work, from condensed matter physics to the highest energies in future colliders such as the SSC of a future linear collider. Advances in the understanding of the physical laws related to spin are being actively supported by the developments in technology having to do with polarized beams, polarized targets, manipulation of spin in accelerators, and polarimetry. Experimental techniques utilizing spin as a tool are alive at almost all accelerator facilities around the world. Significant progress in the past year give evidence to this. LEP at CERN reports that a circulating beam exhibits transverse polarization. TRISTAN at KEK similarly observed transverse polarization and reported a component of longitudinal polarization as well. Evidence for polarization in these large electron storage rings bodes well for the HERA project, which plans for physics runs with polarized beams. Siberian snakes have long been discussed as a means of eliminating spin depolarizing resonances in proton accelerators. The application to electron rings has not been tested, but modified snakes are incorporated into the HERA interaction regions to provide longitudinal spin at the point where electrons and protons collide. These spin rotators will be tested in the near future.

The exciting news comes from the Indiana University Cyclotron Facility where the cooling ring has been equipped with a version of a snake. This project has now demonstrated that snakes can eliminate spin resonances in proton rings, confirming the theoretical predictions.[27]

In the field of polarized sources, new results with electron sources at SLAC[28] and in Japan[29] demonstrate that strained gallium arsenide photoemitters can provide up to 85% polarization for electron beams. These sources can provide high currents, low emittance, and easy spin reversals for continuous wave and pulsed applications in accelerators. In the field of polarized targets, high power highly polarized targets are being developed for protons, neutrons, and a variety of heavier nuclei. Spin technology is providing new and improved tools for the experiments to use. These developments are making it possible to pursue the fundamental laws of matter with new approaches.

Spin remains a fundamental property of matter and in some respects a deep mystery. Advances in theory, experiments, and the tools to study these issues are occurring continually. We look forward to the unravelling of these mysteries and the challenging steps ahead required to accomplish a better and deeper understanding of our universe.

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