I describe a few of the most exciting open questions in high energy spin physics. After a brief look at \((g - 2)_\mu\) and the muon electric dipole moment, I concentrate on QCD spin physics. Pressing questions include the interpretation of new asymmetries seen in semi-inclusive DIS, measuring the polarized gluon and quark transversity distributions in the nucleon, testing the DHGHY Sum Rule, measuring the orbital angular momentum in the nucleon, and many others which go beyond the space and time allotted for this talk.

1. Introduction

I would like to thank the organizers for the opportunity to deliver the opening talk at this exciting conference. When I was last in Beijing in 1981 no one could have predicted what lay just around the corner in the domain of high energy spin physics. The measurement of the quark spin contribution to the nucleon spin by the European Muon Collaboration in the mid-1980s launched a new era in QCD spin physics, which will be the principal focus of my talk.

The organizers asked me to stress open questions. This has its advantages, since they did not require me to provide answers. Recent excitement leads me to mention very briefly some headlines in physics beyond the Standard Model. After that I will get down to the business of QCD. Of necessity, I have singled out a few topics for attention. Other issues of equal, perhaps some would say greater, interest will only be mentioned in passing along with some areas which I have found particularly frustrating. Here is my outline:

(i) Headlines: \(g - 2\) and the muon electric dipole moment

(ii) Focus: High energy spin physics in QCD

   (a) What are the origins and implications of the Hermes azimuthal asymmetry?
   (b) What is the quark transversity distribution in the nucleon?
   (c) What is the polarized gluon distribution in the nucleon?
   (d) Can the Gerasimov-Drell-Hearn-Hosata-Yamamoto Sum Rule fail?

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(e) What can be said about quark and gluon orbital angular momentum in the nucleon?

(iii) In passing... (revisited briefly at the end)

(a) What happens to $g_1(x, Q^2)$ at very low $x$?  
(b) What are the properties of the $s$ and $\bar{s}$ quarks in the nucleon?
(c) What are the spin-dependent quark-gluon correlations in the nucleon?
(d) What is the flavor decomposition of the nucleon’s spin?
(e) How do QCD spin effects behave as $Q^2 \to 0$?
(f) What can “off-forward” parton distributions tell us about hadron properties?
(g) Can some deeper order be found in the proliferation of $\vec{k}_\perp$ and $x$ dependent distribution and fragmentation functions?

2. Headlines: $g - 2$ and the muon electric dipole moment

No discussion of high energy spin physics would be complete without recognizing the important role of spin in precision tests of the Standard Model. Recent headlines include a new high precision measurement of $(g - 2)_\mu = 2a_\mu$ and a proposal to increase the precision on the muon’s EDM by several orders of magnitude.

The muon’s magnetic moment probes certain extensions of the Standard Model up to energies equivalent to LEP and the Tevatron, and is sensitive to SUSY and other novelites. After years of hard work and great patience, the Brookhaven experiment (E821) has reported a value for $a_\mu$ which will challenge the Standard Model. It is conventional to quote values for $a_\mu$ in units of $10^{-10}$ or $10^{-11}$ and accuracy in parts per million. Thus the old CERN $\mu^+$ value of $a_\mu \times 10^{10} = 116.591 \, 00(110)$ has an accuracy of 10 ppm. The number reported from BNL, $a^{\text{BNL}}_\mu \times 10^{10} = 116.592 \, 02(14)(6)$, has an accuracy of 1.3 ppm. The new weighted average of data on $a_\mu$ disagrees with the “standard” theoretical estimate, $a^{\text{TH}}_\mu \times 10^{11} = 116.591 \, 596(67)$ by 2.6 standard deviations. At present the precision of the theoretical estimate of $(g - 2)_\mu$ is principally limited by the lack of information on higher order QCD contributions, which require further study. Approved experiments at BNL plan to reduce the statistical and systematic uncertainties on $a_\mu$ to about 0.3 ppm, making better understanding of the QCD contribution a very high priority.

Electric dipole moments (EDMs) probe CP violation, one of the most poorly understood aspects of the Standard Model. If all CP-violation is encoded in the...
CKM matrix, EDMs are too small to measure. Therefore EDMs are an excellent place to look for CP-violation beyond the Standard Model. Attempts to explain the origin of the baryon excess in the Universe suggest that other sources of CP-violation may be waiting to be discovered. Standard Model (i.e., CKM) predictions for EDMs are far smaller than the reasonable goals of experiments. This need not be the case for interesting alternatives. In fact one might expect a new physics contribution to the anomalous magnetic moment, $a_\mu$ and the EDM, $d_\mu$, to be comparable. More precisely, $a_\mu$ and $d_\mu$ are defined by

$$L_{\text{new}} = \left( \frac{e}{4m_\mu} \right) a_\mu \overline{\mu} \sigma^{\alpha\beta} F_{\alpha \beta \mu} - \frac{i}{2} d_\mu \overline{\mu} \sigma^{\alpha\beta} F_{\alpha \beta \gamma} \gamma^5 \mu$$

so one might expect $a_\mu$ and $2 m_\mu d_\mu / e$ to be in proportion to $\tan \phi_{\text{CP}}$, where $\phi_{\text{CP}}$ is a new CP violating phase. So EDM measurements at a sensitivity comparable to existing limits on $a_\mu$ could provide fertile ground in which to look for new sources of CP-violation. Of particular interest is Semertzidis’s proposal to use the BNL $(g-2)$ ring to improve the limit on the muon EDM by as much as six orders of magnitude beyond the present limit of order $10^{-18}$ e-cm. Taking $\phi_{\text{CP}} \sim 1$, $d_\mu \sim 10^{-22}$ e-cm, so this is an interesting possibility. Readers interested in this simple and elegant idea should consult the review by Khriplovich.

3. Focus: High Energy Spin Physics in QCD

3.1. Origins Implications of the Hermes Azimuthal Asymmetry?

To my mind the single most interesting development in QCD spin physics reported in the past two years is the azimuthal asymmetry in pion electroproduction from Hermes. It is interesting in itself and also as an emblem of a new class of spin measurements involving spin-dependent fragmentation processes, which act as filters for exotic parton distribution functions like transversity.

Fragmentation functions allow us to access and explore the spin structure of unstable hadrons, which cannot be used as targets for deep inelastic scattering. Examples include the longitudinal and transverse spin dependent fragmentation functions of the $\Lambda$, schematically $\vec{q}_|| \to \vec{\Lambda}_||$ and $\vec{q}_\perp \to \vec{\Lambda}_\perp$. Since the $\Lambda \to p\pi$ decay is self-analyzing it is relatively easy to measure the spin of the $\Lambda$. By selecting $\Lambda$’s produced in the current fragmentation region one can hope to isolate the fragmentation process $q \to \Lambda$. Another, perhaps less obvious, example is the tensor fragmentation function of the $\rho$, denoted schematically by $(q \to \rho_\pm) - (q \to \rho_0)$, where $\rho_h$ are $\rho$ helicity states. $\rho$ decay transmits no spin information, but it distinguishes the longitudinal and transverse helicity states required for this measurement. Such data are already available. The challenge to theorists is to make use of it.

Even if we do not know how to interpret fragmentation functions, we can use them as filters, to select parton distribution functions which decouple from completely inclusive DIS. The salient example is the use of a helicity flip fragmentation
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Fig. 1.

function to select the quark transversity distribution. As shown in Fig. 1, by interposing a helicity flip fragmentation function on the struck quark line in DIS, it is possible to access the transversity (see below). There are several candidates for the necessary helicity flip fragmentation function:

(i) $e\vec{p}_\perp \rightarrow e'\Lambda\vec{K}_\perp X$

In this case the helicity flip fragmentation function of the $\Lambda$ is exactly analogous to the transversity distribution function in the nucleon. The only difficulty with this example is the relative rarity of $\Lambda$’s in the current fragmentation region, and the possibly weak correlation between the $\Lambda$ polarization and the polarization of the $u$ quarks which dominate the proton.

(ii) $e\vec{p}_\perp \rightarrow e'\pi(k\perp)X$ [The “Collins Effect”]

In this case the azimuthal angular distribution of the pion relative to the $q\perp$ axis can be analyzed to select the interference between pion orbital angular momentum zero and one states. This observable correlates with quark helicity flip. In more traditional terms the effect is proportional $\vec{S}_\perp \cdot \vec{q} \times \vec{p}_\pi$. This is multiplied by the quark transversity in the target and an unknown fragmentation function (known as the Collins function) describing the propensity of the quark to fragment into a pion in a superposition of orbital angular momentum zero and one states. The fact that fragmentation functions depend on $z$ while distribution functions depend on $x$ allows the shape of the transversity distribution to be measured in this manner.

(iii) $e\vec{p}_\perp \rightarrow e'\pi\pi X$

In this case the angular distribution of the two pion final state substitutes for the azimuthal asymmetry.

Last year Hermes announced the observation of an azimuthal asymmetry similar to the Collins asymmetry described above, but with a longitudinally polarized target: $e\vec{p}_\parallel \rightarrow e'\pi(k\perp)X$. Their data are shown in T. Shibata’s contribution to this conference. This asymmetry could be a (suppressed) reflection of the Collins effect because the target spin, while parallel to the electron beam, has a small component, $O(1/Q)$ perpendicular to the virtual photon. It could also result from competing twist-three helicity flip effects also suppressed by $1/Q$. Unless the Hermes asymmetry is entirely twist-three, which seems unlikely, it appears that the prospects for observing a large azimuthal asymmetry from a transversely polarized target are very good. Hermes will be running with a transversely polarized target this year and
their results will be awaited with considerable excitement. COMPASS has similar objectives. The spin program at RHIC hopes to access transversity by observing a similar \((\pi\pi)\) azimuthal asymmetry in \(pp\) collisions.

### 3.2. The Quark Transversity Distribution in the Nucleon?

One of the major accomplishments of the recent renaissance in QCD spin physics has been the rediscovery and exploration of the quark transversity distribution. First mentioned by Ralston and Soper in 1979 in their treatment of Drell-Yan \(\mu\)-pair production by transversely polarized protons, the transversity was not recognized as a major component in the description of the nucleon’s spin until the early 1990s. We now know that the transversity, \(\delta q(x, Q^2)\), together with the unpolarized distribution, \(q(x, Q^2)\), and the helicity distribution, \(\Delta q(x, Q^2)\), are required to give a complete description of the quark spin in the nucleon at leading twist. One equation tells this story clearly:

\[
\mathcal{A}(x, Q^2) = \frac{1}{2} q(x, Q^2) I \otimes I + \frac{1}{2} \Delta q(x, Q^2) \sigma_3 \otimes \sigma_3 + \frac{1}{2} \delta q(x, Q^2) (\sigma_+ \otimes \sigma_- + \sigma_- \otimes \sigma_+) \tag{2}
\]

Here, \(\mathcal{A}\) is the quark distribution in a nucleon as a density matrix in both the quark and nucleon helicities (hence the direct product of two Pauli matrices in each term). \(q\) governs spin average physics, \(\Delta q\) governs helicity dependence, and \(\delta q\) governs helicity flip – or transverse polarization – physics.

The transversity can be interpreted in parton language as the probability to find quarks of momentum fraction \(x\), transversely polarized in a transversely polarized nucleon at infinite momentum. The quark momentum distribution is well known and the helicity distribution is becoming better known. In contrast nothing is known about transversity from experiment, because it decouples from inclusive DIS on account of a selection rule. At leading twist helicity and chirality are identical. Transversity corresponds to helicity, and therefore chirality, flip. So transversity decouples from processes with only vector or axial vector couplings. In order to access transversity it is necessary to flip a quark’s helicity and then flip it back in two soft processes. Two examples where transversity does not decouple are transversely polarized Drell-Yan: \(\vec{p}_\perp \cdot \vec{p}_\perp \rightarrow \mu^+ \mu^- X\) (the original Ralston-Soper process where transversity was discovered) and semi-inclusive DIS where a final state fragmentation function flips helicity, \(e\vec{p}_\perp \rightarrow e'\vec{h}_\perp X\), as shown in Fig. 1. Measurements of quark transversity rank high on the agendas of Hermes, COMPASS and RHIC.

### 3.3. The Polarized Gluon Distribution in the Nucleon?

A direct measurement of the polarized gluon distribution in the nucleon is probably the highest priority for QCD spin physics. The first, indirect estimates of \(\Delta G(x, Q^2)\) have been made by the SMC group by studying the \(Q^2\) dependence of the quark distribution, \(\Delta q(x, Q^2)\), which couples to \(\Delta G\) through renormalization group evolution. [See Ref. for details of the process and references to the original literature.]
Further refinement of the indirect method will improve our knowledge of $\Delta G$, but direct measurement is essential to determine gross features of its shape.

Several direct methods are being pursued:

(i) $\bar{c}c$ pair production in $e\bar{p}_\parallel \rightarrow e'(\bar{c}c)X$ and related methods.

The COMPASS Collaboration has proposed to extend this powerful probe of the unpolarized gluon distribution to the polarized case. The basic mechanism is photon-gluon fusion. Variations on this method include two jet production: $e\bar{p}_\parallel \rightarrow e'\text{jet jet }X$ at large transverse momentum (as originally envisioned by Carlitz, Collins, and Mueller); $\bar{c}c$ photoproduction $\gamma\bar{p}_\parallel \rightarrow (\bar{c}c)X$; and pion pair production, $\gamma\bar{p}_\parallel \rightarrow \pi\pi X$, which Hermes hopes to use at lower center of mass energies where $\bar{c}c$ and two jet production are not available.

(ii) Single photon production at high transverse momentum in polarized $\bar{p}_\parallel\bar{p}_\parallel \rightarrow \gamma\text{ jet }X$ and related methods.

This is a prime goal for the polarized proton program at RHIC. Here the basic mechanism is the QCD Compton process. This process should be an excellent probe of the polarized gluon distribution. However there is some controversy about higher order QCD corrections which has yet to be resolved in the unpolarized case. Variations replace the high energy photon with a jet, or in the case of poor jet acceptance, a leading pion at high transverse momentum.

Estimates of the precision of these methods have become available as better simulations come on line for COMPASS and RHIC. For detailed projections see the talks by T. Morii, N. Saito, and T. Shibata in these proceedings.

### 3.4. The Gerasimov-Drell-Hearn-Hosada-Yamamoto Sum Rule?

The prospects for a definitive test of this deep and ancient sum rule are now excellent. Old studies of resonance contributions to the sum rule indicate that the sum rule is approximately saturated, but data in the Regge region are crucial. Experiments proposed and/or underway in Bonn (at ELSA), Mainz (at MAMI) and at JLab will cover a wide range of energies with high polarization and high statistics. The question I would like to raise here is “What does the DHGHY Sum Rule test?”. The sum rule reads

$$\frac{2\pi^2\alpha}{M^2}\kappa^2 = \int_0^\infty \frac{d\nu}{\nu}(\sigma_P(\nu) - \sigma_A(\nu))$$

where $\kappa$ and $M$ are the anomalous magnetic moment and mass of the target, and $\sigma_{P,A}$ are the total photoabsorption cross sections (as functions of the laboratory photon energy, $\nu$) for target and photon spins parallel and antiparallel.

The sum rule rests on two assumptions: first Low’s low energy theorem $f_2(0) = -\frac{1}{2} \frac{\alpha}{M^2}\kappa^2$, where $f_2(0)$ is the energy derivative of nucleon’s forward spin-flip Compton amplitude at zero energy and second, the assumption that $f_2(\nu)$ obeys an
unsubtracted dispersion relation. Low’s theorem relies only on gauge invariance and analyticity, and is not expected to be violated. The dispersion relation reads

\[ \text{Re } f_2(\nu) = \sum_{j=0}^{J_{\text{MAX}}} c_j \nu^{2j} + \frac{1}{8\pi^2} \text{P} \int_0^\infty \frac{\sigma_A(\nu') - \sigma_P(\nu')}{\nu'^2 - \nu^2} \, d\nu'. \]  

The polynomial is usually omitted in writing the dispersion relation, however it is not excluded by analyticity or unitarity. Then the sum rule is obtained by combining the dispersion relation with the low energy theorem.

What could go wrong with this? Absent any problems with electrodynamics, the only weak point is ignoring the possible polynomial in the dispersion relation. Only the constant term \((c_0)\) in the polynomial matters at \(\nu = 0\). Usually limits on the growth of amplitudes at high energies are invoked to exclude the \(\{c_j\}\) with \(j \geq 1\). However, they do not exclude the constant, \(c_0\). If the integral in eq. 4 diverged it would be necessary to reformulate it by formally subtracting \(f_2(0)\). The resulting integral would be more convergent, but now the constant \(f_2(0)\) would appear in the relation. However, even if the integral in eq. 4 converges, still the constant \(c_0\) could be non-zero and spoil the sum rule. Such a constant is called, for historical reasons, a “\(J = 1\) fixed pole”. So the question of the validity of the DHGHY Sum Rule comes down to whether \(J = 1\) fixed poles occur in QCD. It is known that they do not occur in low orders of perturbation theory. This was first verified when the electroweak anomalous magnetic moment of the muon was calculated (for the first time!) using a generalization of these methods. Subsequently it has been studied to higher orders. Brodsky and Primack have argued that it does not occur in ordinary bound states. They show that the anomalous magnetic moment of hydrogen can be calculated from a generalized DHGHY Sum Rule with out a \(J = 1\) fixed pole. Still, the verdict is out in QCD, where bound states are not so simple.

If the DHGHY Sum Rule is verified experimentally, this question will recede to a footnote to history. If, however, experiment fails to confirm it, we will all have a lot to learn about \(J = 1\) fixed poles!

3.5. Orbital angular momentum in QCD?

Even in the old days (pre-1988), it was clear that quark and gluon spin distributions could be measured in deep inelastic scattering. In some uncertain sense they were imagined to be part of a relation which gave the nucleon’s helicity, \(\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta g + [\text{the rest}]\) where “the rest” was not well understood. \(\Delta \Sigma\) and \(\Delta g\) were (and are) measurable, gauge invariant, and given by integrals over \(x\) of well-defined quark and gluon distribution functions. Significant progress occurred in the late ‘80s and ‘90s as the other pieces of the angular momentum were related to local, gauge invariant operators. This line of work culminated in Ji’s decomposition of the nucleon’s helicity, \(\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \hat{L}_q + \hat{J}_g\) where \(\hat{L}_q\) is the nucleon matrix element of an operator that rotates quarks’ orbital motion about the \(\hat{e}_3\)-axis in the rest frame. \(\hat{J}_g\) is the nucleon matrix element of the operator that rotates the gluon
about the $\hat{e}_3$ axis. Ji showed that $\hat{J}_g$ cannot be further decomposed into $\Delta g$ and an orbital contribution given by a local gauge invariant operator. This should not be too surprising because it is well known that $\Delta g$ itself cannot be expressed in terms of a local gauge invariant operator. [In general the operator is non-local, but becomes local in $A^+=0$ gauge.] The virtue of Ji’s decomposition is that $\hat{L}_q$ can be measured in deeply virtual Compton scattering (DVCS). Although $\hat{J}_g$ is in principle also measurable in DVCS, it requires a precision study of $Q^2$ evolution DVCS data and is impossible for practical purposes.

Most recently it has been possible to define gauge invariant parton distributions for all the components of the nucleon’s angular momentum:

$$\frac{1}{2} = \int_0^1 dx \left\{ \frac{1}{2} \Delta \Sigma(x, Q^2) + \Delta g(x, Q^2) + L_q(x, Q^2) + L_g(x, Q^2) \right\}$$

where $L_q$ and $L_g$ are Bjorken-$x$ distributions of quark and gluon orbital angular momentum in the infinite momentum frame. $L_q$ and $L_g$ are given by the light-cone fourier transforms of bilocal operator products just like other parton distributions. This decomposition has many virtues: the four terms evolve into one another with $Q^2$, each term is the Noether charge associated with the appropriate transformation of quarks or gluons. Thus $L_g(x, Q^2)$ is the observable associated with the orbital rotation of gluons with momentum fraction $x$, about the infinite momentum axis in an infinite momentum frame. On the other hand, eq. (5) suffers from a significant drawback: unlike Ji’s $\hat{L}_q$, we know of no way to measure either $L_q(x, Q^2)$ or $L_g(x, Q^2)$. They do not appear in the description of DVCS.

So the situation with respect to a complete description of the nucleon’s angular momentum is frustrating. The theory is under control. Eq. (5) summarizes all we would like to know, but we do not know how to measure what we would like. For a more complete review, see the talk by X. Ji in these proceedings.

4. Noted in Passing…

4.1. $g_1(x, Q^2)$ at low-$x$

Reasonable extrapolations of existing data suggest that both $g_{1p}$ and $g_{1n}$ are negative and diverge as $x \to 0$. This has little effect on the spin sum rules, but belongs to the new, interesting low-$x$, strong coupling regime of QCD.

4.2. $s$ and $\bar{s}$ quarks in the nucleon

Strange quarks carry both momentum and spin in the nucleon. The strange quark’s contribution to the nucleon spin can be extracted from polarized DIS, hyperon $\beta$ decay data, and SU(3) symmetry. The strange quark’s contribution to the nucleon’s momentum is measured from dimuon production in neutrino DIS. These are both
C-even observables and therefore add quarks and antiquarks. Parity violating electron scattering at low energy is sensitive to the strange quark contribution to the nucleon’s magnetization ($\mu_s$) and charge radius ($\langle r_s^2 \rangle$), both C-odd, and therefore sensitive to $s - \bar{s}$. Both SAMPLE and HAPPEX report measurements, albeit with large uncertainties, consistent with zero. Theorists predict non-zero values for both $\mu_s$ and $\langle r_s^2 \rangle$ near the limits of experimental sensitivity. The next round of experiments should tell us whether $s$ and $\bar{s}$ quarks in the nucleon have significantly different spatial distributions.

4.3. Spin dependent quark gluon correlations in the nucleon
The first high statistics measurements of the twist-three structure function, $g_2(x, A^2)$, for both the proton and neutron have been reported by E155x at SLAC. For a complete review see the talk of P. Bosted in these proceedings. The matrix elements of quark-gluon correlations can be extracted from these data. They appear very small. Perhaps dynamical higher twist is always small. If so, DIS data could be extrapolated to very low $Q^2$ by including only kinematic higher twist. This approach, first suggested (for $g_2$) by Wandzura and Wilczek, would be a framework for connecting low-$Q^2$ data with the DIS regime. The generalized Wandzura-Wilczek approximation offers the promise of a solid theoretical foundations for speculations about “parton-hadron duality” in low energy lepton scattering.

4.4. Off-forward parton distributions
Following the groundbreaking work by Ji, the concept of a parton distribution function has been generalized away from the forward direction. Ji, Radyushkin and others have shown that these “skewed” parton distributions can be measured (with considerable effort) in deeply virtual Compton scattering (DVCS). I mentioned one physical application earlier in connection with the concept of parton orbital angular momentum. Many talks at this conference are devoted to these new distributions. What is missing so far, to my taste, is a heuristic understanding of the physical significance of off-forward parton distributions. We still need to figure out exactly what they are and what will we learn by measuring them.

4.5. Proliferation
In response to new measurements of detailed properties in DIS ($k_\perp$ distributions, higher twist, semi-inclusive processes), theorists have introduced a wonderful new zoo of distribution and fragmentation functions. Now we need some clever zoology to classify, relate, and interpret these new functions. Are they all independent or are they related to one another by as yet unappreciated symmetries? What is the

$^d$Parity violating $(xF_3)$ dimuon production in neutrino DIS can, in principle, separate $s$ and $\bar{s}$ momentum distributions. Present data are not accurate enough to differentiate $s$ and $\bar{s}$. 
general physical interpretation of fragmentation functions analogous to the parton model of distribution functions? Perhaps some of them need to become extinct?

How useful is the Wandzura-Wilczek approximation, which systematically ignores dynamical higher twist?

5. Conclusions

My conclusions are brief. We have made striking progress in recent years. The prospects for further progress are excellent both in the immediate future and in the long term.

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