INTRODUCTION TO HIGH-ENERGY SPIN PHYSICS

XIANGDONG JI

Department of Physics
University of Maryland
College Park, Maryland 20742

High-energy spin physics has emerged as an important subfield of hadron physics since the EMC measurement of the quark contribution to the spin of the nucleon fifteen years ago. In this introductory talk, I discuss a few topics of recent interest: polarized gluon distribution, generalized parton distributions and deep-virtual Compton scattering, and transversity distribution.

Let me start by thanking the colleagues at UVa for organizing this wonderful workshop. The experimentalists at the Institute of Nuclear and Particle Physics here have made impressive contributions to the field of high-energy spin physics in the last decade. They played a significant role in a series of SLAC experiments which have laid the foundation for our understanding of the spin structure of the nucleon today.

This is supposed to be an introductory talk. However, it would be impossible for me to cover all of the many interesting subjects which will be discussed in the course of the workshop. Instead, I will focus on a few topics in high-energy spin physics which I have personally involved with. The outline of the presentation is as follows: I start with a big question and discuss the lesson we learned from the EMC measurements. Following this, I introduce the gluon helicity distribution and discuss its measurements in the near future. A major part of my talk will be devoted to the spin structure of the nucleon and related topics such as generalized parton distributions and deep exclusive processes such as deeply-virtual Compton scattering (DVCS). Towards the end of my talk, I briefly review the current understanding about the transversity distribution.

One of the most important and difficult questions in modern physics is how is the nucleon (or hadronic matter) made of quarks and gluons? Unlike the question about the existence of quark-gluon plasma or Higgs bosons, the answer does not lie in a single set of experiments or a single

set of theoretical calculations. How does one make progress then? Experimentally, we need high-precision measurements of observables such as the neutron electromangetic form factors, the strange quark form factors, and deep-inelastic spin asymmetries as $x_{bj} \to 1$. We also need to explore new hadronic physics phenomena like the existence of glueballs and exotics, and to understand new processes such as deeply virtual Compton scattering. The polarization is a new dimension in which we can explore a multitude of new observables and interesting effects. In the theoretical frontier, we need to develop better tools such as lattice QCD and effective theories. Above all, we must ask important and relevant questions and try our best to answer them.

Nearly fifteen years ago, it was found from the EMC experiment that the fraction of the nucleon spin carried in the quark spin was [1]

$$\Delta\Sigma \ll 1 \ . \tag{1}$$

What is the single most important lesson we have learned to date? My answer is that the nucleon is much more complicated than the naive quark model depicts. It forces us to understand the internal structure of the nucleon from the fundamental theory of the strong interactions, quantum chromodynamics (QCD). At the phenomenological level, one may regard the quark model as an effective description but it is of little use for understanding deep-inelastic scattering if one does not understand the relation between the QCD quarks and the constituent quarks. The major experimental accomplishment in the last decade is that the EMC result has now been solidly confirmed by SMC, E142/E143, E154/E155, and HERMES experiments. [See ref. [2] for a summary and see talks by Lichtenstadt, Cates, Beckmann and Meziani in this proceeding.]

One of the most important questions in the field of QCD spin physics remains: where does the nucleon get its spin? We know that QCD offers additional sources of angular momentum besides the quark spin: There is a gluon helicity contribution Δg; quark and gluon orbital motion also contribute. The challenge we face now is to find these additional contributions experimentally. Theoretically, one has to incorporate these contributions into a field-theoretical framework for the spin structure of the nucleon. A challenge for theorists is to find ways to calculate the contributions directly from QCD.

What is the gluon helicity distribution? It is well defined theoretically (gauge-invariant but scale-dependent,) just like the quark helicity distribu-

tion,

$$\Delta g(x) = \frac{i}{2x} \int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle PS | F^{+\alpha}(0) L(0, \lambda n) \tilde{F}^{+}_{\alpha}(\lambda n) | PS \rangle \ , \tag{2}$$

where $L(0, \lambda)$ is the standard light-cone gauge link. Its role in the angular momentum sum rule, however, is not entirely clear because its first moment does not correspond to a local operator. Only in the light-cone gauge does the operator reduces to a gluon helicity operator. Then Δg can be interpreted as the gluon helicity contribution to the proton spin. Measuring and understanding this quantity is a high priority in the future high-energy spin physics (see talks by Perdekamp, Bosted and Stratmann et al. in this proceeding).

What do we know about $\Delta g(x)$? According to the QCD evolution of the $g_1(x, Q^2)$ structure function, one can extract it from the polarized DIS data. The SLAC and HERMES data cover an average $Q^2 \sim$ 3-5 GeV^2. On the other hand, the EMC and SMC data span an average Q^2 of 10 GeV^2. A typical next-to-leading order QCD fit yields [2]

$$\int \Delta g(x, Q^2 = 1\text{GeV}^2) dx = (1.0 \pm 1.0)\hbar \ , \tag{3}$$

where I have been generous on the error bar because the fits depend on the unknown form of the gluon distribution. Almost all the fits in the literature assume that the gluon distribution has the same sign throughout the x range. An interesting question is what if it has a sign change somewhere? Recently, the HERMES collaboration has reported a direct measurement of $\Delta g(x)$ from large p_t hadron production,

$$\Delta g(x)/g(x) = 0.41 \pm 0.18 \pm 0.03 \tag{4}$$

at an average gluon $x = 0.17$ [3]. One question I have is why the gluon helicity contributes so much to the spin of the nucleon if the constituent quark model works so well.

There are many plans for future measurements. At CERN, the COMPASS collaboration will measure Δg from the open charm production and high-P_t hadron production [4]. The RHIC spin collaboration will extract Δg from direct photon production, jet and high p_t hadron productions, and heavy quark production [5]. A new experiment at SLAC will also study open charm production in polarized photon-nucleon (LiD target) scattering [6]. The planned electron-ion collider in the United States is capable of measuring Δg through Q^2 evolution of the structure functions, and jet and high p_t hadron productions [7]. A combined analysis of the future data

promises a fairly accurate determination of the first moment of the gluon helicity. One important theoretical question is whether the perturbative QCD mechanism works well under these experimental conditions.

To understand the spin structure of the nucleon in the framework of quantum chromodymics (QCD), one considers the QCD angular momentum operator in its gauge-invariant form [8]

$$\vec{J}_{\rm QCD} = \vec{J}_q + \vec{J}_g \,, \tag{5}$$

where

$$\begin{aligned} \vec{J}_q &= \int d^3x \; \vec{x} \times \vec{T}_q \\ &= \int d^3x \; \left[\psi^\dagger \frac{\vec{\Sigma}}{2} \psi + \psi^\dagger \vec{x} \times (-i\vec{D})\psi \right] \,, \\ \vec{J}_g &= \int d^3x \; \vec{x} \times (\vec{E} \times \vec{B}) \,. \end{aligned} \tag{6}$$

The quark and gluon parts of the angular momentum are generated from the quark and gluon momentum densities $\vec{T}_q$ and $\vec{E} \times \vec{B}$, respectively. $\vec{\Sigma}$ is the Dirac spin-matrix and the corresponding term is the quark spin contribution. $\vec{D} = \vec{\nabla} - ig\vec{A}$ is the covariant derivative and the associated term is the gauge-invariant quark orbital contribution.

With the above expression, one can easily construct a sum rule for the spin of the nucleon. Consider a nucleon moving in the z-direction, and polarized in the helicity eigenstate $\lambda = 1/2$. The total helicity can be evaluated as an expectation value of J_z in the nucleon state,

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + J_g(\mu) \,, \tag{7}$$

where the three terms denote the matrix elements of three parts of the angular momentum operator in Eq. (6). The physical significance of each term is obvious, modulo the scale and scheme dependence indicated by μ. The scale dependence in $\Sigma(\mu)$ is generated from the U(1) axial anomaly. Note that the individual term in the above equation is independent of the momentum of the nucleon. In particular, it applies when the nucleon is travelling with the speed of light (the infinite momentum frame) [9].

By examining carefully the definition of $J_{q,g}$

$$J_{q,g}(\mu) = \left\langle P\frac{1}{2} \left| \int d^3x (\vec{x} \times \vec{T}_{q,g})^z \right| P\frac{1}{2} \right\rangle \,, \tag{8}$$

one realizes that they can be extracted from the form factors of the quark and gluon parts of the QCD energy-momentum tensor $T^{\mu\nu}_{q,g}$. Using Lorentz and discrete symmetry, we obtain

$$\langle P'|T^{\mu\nu}_{q,g}|P\rangle = \overline{U}(P')\ \Big[\ A_{q,g}(t)\gamma^{(\mu}\overline{P}^{\nu)} + B_{q,g}(t)\overline{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha/2M + C_{q,g}(t)\Delta^{(\mu}\Delta^{\nu)}/M\Big]U(P)\,. \tag{9}$$

Taking the forward limit in the $\mu = 0$ component and integrating over 3-space, one finds that $A_{q,g}(0)$ give the momentum fractions of the nucleon carried by quarks and gluons ($A_q(0) + A_g(0) = 1$). On the other hand, substituting the above into the nucleon matrix element of Eq. (8), one finds [8]

$$J_{q,g} = \frac{1}{2}\left[A_{q,g}(0) + B_{q,g}(0)\right]\,. \tag{10}$$

Therefore, the matrix elements of the energy-momentum tensor provide the fractions of the nucleon spin carried by quarks and gluons. There is an analogy for this. If one knows the Dirac and Pauli form factors of the electromagnetic current, $F_1(Q^2)$ and $F_2(Q^2)$, the magnetic moment of the nucleon, defined as the matrix element of $(1/2)\int d^3x(\vec{x}\times\vec{j})^z$, is $F_1(0) + F_2(0)$.

The form factors of the energy-momentum tensor can be extracted from the generalized parton distributions (GPD) [8,10]. GPDs are a new type of parton distributions which contain much more information than any other nucleon observables that have been considered so far. They are defined through the matrix elements of a bilocal light-cone operator,

$$\begin{aligned}&\frac{1}{2}\int\frac{d\lambda}{2\pi}e^{i\lambda x}\left\langle P'\left|\overline{\psi}_q\left(-\frac{\lambda}{2}n\right)\ \not{n}\mathcal{P}e^{-ig\int_{\lambda/2}^{-\lambda/2}d\alpha\ n\cdot A(\alpha n)}\psi_q\left(\frac{\lambda}{2}n\right)\right|P\right\rangle\\ &= H_q(x,\xi,t)\ \frac{1}{2}\overline{U}(P')\ \not{n}U(P) + E_q(x,\xi,t)\\ &\quad\times\frac{1}{2}\overline{U}(P')\frac{i\sigma^{\mu\nu}n_\mu\Delta_\nu}{2M}U(P)\,.\end{aligned} \tag{11}$$

The light-cone bilocal operator (or light-ray operator) arises frequently in hard scattering processes in which partons propagate along the light-cone. In fact, the Taylor-expansion of this operator along the light-cone leads us immediately to the twist-two operators which include the energy-momentum tensor of the quarks. The parton distributions are most naturally defined in terms of the matrix elements of the bilocal operator. In this context, the Feynman x is just the conjugating Fourier variable of the light-cone distance. The Lorentz structures in the second line in the above

equation are independent and complete. In various limits, they reduce to elastic form factors and Feynman parton distributions.

The GPD's are more complicated than the Feynman parton distributions because of their dependence on the momentum transfer Δ. As such, they contain two more scalar variables besides the Feynman variable x. The variable t is the usual t-channel invariant which is always present in a form factor. The ξ variable is a natural product of marrying the concepts of the Feynman distribution and form factor: The former requires the presence of a preferred momentum p^μ along which the partons are predominantly moving, and the latter requires a four-momentum transfer Δ; ξ is just a scalar product of the two momenta.

Since the quark and gluon energy-momentum tensors are just the twist-two, spin-two, parton helicity-independent operators, we immediately have the following sum rule for the off-forward distributions;

$$\int_{-1}^{1} dx x[H_q(x,\xi,t) + E_q(x,\xi,t)] = A_q(t) + B_q(t)\,, \tag{12}$$

where the ξ dependence, or $C_q(t)$ contamination, drops out. Extrapolating the sum rule to $t = 0$, the total quark (and hence quark orbital) contribution to the nucleon spin is obtained. A similar sum rule exists for gluons. Thus a deep understanding of the spin structure of the nucleon may be achieved by measuring the GPDs from high energy experiments.

Recently, M. Burkardt has constructed an interpretation of GPD in the coordinate space [11]. Consider the nucleon state localized in a transverse plane at $r_\perp = 0$,

$$|p^+, r_\perp = 0\rangle = N \int d^2p_\perp |p^+, p_\perp\rangle\ , \tag{13}$$

where N is a normalization factor. Define a parton distribution $q(x, b_\perp)$ which is the density of partons with longitudinal momentum xp^+ and the transverse distance $b_\perp$ in the state,

$$q(x, b_\perp) = \int \frac{d\lambda}{4\pi} \langle p^+, r_\perp|\overline{\psi}(0,b)\gamma^+\psi(\lambda n, b)|p^+, r_\perp\rangle e^{ix\lambda}. \tag{14}$$

Then it can be shown that $q(x, b)$ is the Fourier transformation of $H(x, -\Delta_\perp^2, \xi = 0)$ with respect to the transverse momentum transfer,

$$q(x, b) = \int d^2\Delta_\perp H(x, -\Delta_\perp^2) e^{ib\cdot\Delta_\perp}\ . \tag{15}$$

Thus the GPDs provide the transverse locations of the partons in the nucleon.

Usefulness of the GPD concept depends on whether they can actually be measured in any experiment. The simplest, and possibly the most promising, type of experiments are the hard electro- or deep-inelastic production of photons, mesons, and perhaps even lepton pairs. In the following, we will consider separately two experiments: deeply virtual Compton scattering (DVCS) in which a real photon is produced, and diffractive meson production. There are practical advantages and disadvantages from both processes. Real photon production is, in a sense, cleaner but the cross section is reduced by an additional power of $\alpha_{\rm em}$. Moreover, the DVCS amplitude interferes with the Bethe-Heitler one. Meson production may be easier to detect, however, it has a twist suppression, $1/Q^2$. In addition, the theoretical cross section depends on the unknown light-cone meson wave function.

Deeply virtual Compton scattering was proposed in Ref. [8] as a practical way to measure the off-forward distributions. Consider the virtual photon scattering in which the momenta of the incoming (outgoing) photon and nucleon are $q(q')$ and $P(P')$, respectively. The Compton amplitude is defined as

$$T^{\mu\nu} = i \int d^4 z e^{\bar{q}\cdot z} \left\langle P' \left| \mathrm{T} J^\mu \left(-\frac{z}{2}\right) J^\nu \left(\frac{z}{2}\right) \right| P \right\rangle \tag{16}$$

where $\overline{q} = (q+q')/2$. In the Bjorken limit, $-q^2$ and $P\cdot q \to \infty$ and their ratio remains finite, the scattering is dominated by the single quark process in which a quark absorbs the virtual photon, immediately radiates a real one, and falls back to form the recoiled nucleon. In the process, the initial and final photon helicities remain the same. The leading-order Compton amplitude is

$$\begin{aligned} T^{\mu\nu} = g_\perp^{\mu\nu} \int_{-1}^{1} dx \left(\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon} \right) \sum_q e_q^2 F_q(x,\xi,t,Q^2) \\ + \; i\epsilon^{\mu\nu\alpha\beta} p_\alpha n_\beta \int_{-1}^{1} dx \left(\frac{1}{x-\xi+i\epsilon} - \frac{1}{x+\xi-i\epsilon} \right) \\ \times \sum_q e_q^2 \tilde{F}_q(x,\xi,t,Q^2)\,, \end{aligned} \tag{17}$$

where n and p are the conjugate light-cone vectors defined according to the collinear direction of $\overline{q}$ and $\overline{P}$, and $g_\perp^{\mu\nu}$ is the metric tensor in the transverse space. ξ is related to the Bjorken variable $x_B = -q^2/(2P\cdot q)$ by $x_B = 2\xi/(1+\xi)$.

Evidence for DVCS was first seen at HERA by H1 and Zeus collaboration [12,13]. More recently, the HERMES collaboration at HERA and CLAS collaboration at JLab have measured the single spin asymmetry from the interference of DVCS and Bethe-Heitler amplitudes [14,15]. More experiments on DVCS will be done in the future at HERA, CERN, and Jefferson Lab.

An all-order proof of the DVCS factorization was first given by Radyushkin [16] and recently in a different perspective by Osborne and Ji [17], and Collins and Freund [18]. Factorization concerns separation of soft physics at the scale of hadron masses and perturbative physics at the scale of probe in the DVCS amplitude. This can be done at the same level as for inclusive DIS. Therefore experimental cross sections can be used to directly extract GPDs. This is nontrivial because the final photon here is on-shell. Technically, it amounts to show all soft physics either can be absorbed into the GPDs, which are nonperturbative anyway, or are down by powers of $1/Q^2$. The factorization result can be formulated in terms of an operator product expansion familiar in the field theory textbooks.

The next-to-leading order corrections to DVCS are important for a precision extraction of GPDs and for an estimate of scaling violation. The complete result is now known. The one-loop corrections to DVCS have first been studied by Osborne and Ji [17], and also by Belitsky and Mueller [19]. Two-loop anomalous dimensions were obtained by Belitsky and Muller [20]. It is the same as that for inclusive DIS except for the non-diagonal contribution which can be determined by one-loop conformal anomaly. Classical chromodynamics is invariant under comformal symmetry which is broken by quantum mechanical effects. Because of this an operator can acquire a scaling dimension under the spatial conformal transformation (conformal anomaly). The size for the NLO corrections has been estimated in [21].

The leading higher-twist contribution to DVCS comes from twist-three longitudinal photon scattering. In the interference amplitude, the imaginary part has a characteristic $\sin 2\phi$ and real part $\cos 2\phi$ dependence. The contribution can be estimated in the so-called Wilczek-Wendzura approximation (neglecting dynamical higher-twist effects). Belitsky, Mueller, and Kirchner et al [24] found that the correction to the single spin asymmetry from the beam polarization is about 6% and from the target polarization is about 9%. For the spin-averaged cross section it is 17% and 3% for the double spin asymmetry.

DVCS can be generalized to the case of exclusive production of mesons [22]. With the virtual photon and vector meson both polarized longitudinally,

one finds

$$\frac{d\sigma}{dt}\ (\gamma^* N \to VN) = \frac{4\pi\Gamma_V m_V \alpha_s^2(Q)\eta_V^2}{3\alpha_{\rm em} Q^6} \times \left| 2x_B \int_{-1}^{1} dx \left(\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon} \right) F_g(x,\xi,t) \right|^2 , \quad (18)$$

where again $x_B = 2\xi/(1+\xi)$. The above formula is valid for any x_B and t smaller or around hadron mass scales. Collins, Frankfurt and Strikman have shown that the deep-exclusive meson production is factorizable to all orders in perturbation theory [23]. The vector meson production entails a rich spin and flavor structure. For example, the vector meson production is sensitive to quark-helicity-independent distributions, whereas the pseudo-scalar mesons are sensitive to quark helicity-dependent distributions. The next-to-leading order perturbative QCD corrections for pseudo-scalar meson production have first been calculated by Belitsky and Mueller [24].

Recently, it has been found that a quantity very sensitive to the quark angular momentum is the target transverse spin asymmetry for vector meson production [25].The asymmetry comes from the interference of two DVCS amplitudes and is linear in the $E(x,\xi,t)$ distribution. Since the asymmetry involves the ratio, it is insensitive to the next-to-leading order and higher-twist effects. The vector meson final state allows separation of different quark flavors. For example, the ρ^0 production is sensitive to the combination $2J_u + J_d$, the ω meson is sensitive to $2J_u - J_d$, and finally the ρ^+ meson is sensitive to the $J_u - J_d$ combination.

Finally, I discuss briefly the transversity distribution which is one of the three twist-two quark distributions describing the state of the quark beam in a nucleon beam [26,27]. It has often been called transverse spin distribution. However, a transversely-polarized spin-1/2 particle does not have definite transverse spin (angular momentum), and hence the usual name is misleading. In addition, there is no simple transverse spin sum rule. [Transverse polarization as defined through the Pauli-Lubanski vector involves angular momentum as well as boost operators.] In non-relativistic quark model, however, the transversity distribution is the same as the helicity distribution because the quarks can now be in the transverse spin eigenstates. The transversity distribution allows access to the so-called tensor charge of the nucleon [27]. See talks about the transversity distribution by Drago, Bianchi, Perdekamp, and Stratmann in this proceeding.

Experimental measurement of transversity distribution $\delta q(x)$ is difficult. This is mainly because it is a chiral-odd quantity, requiring another chiral-

odd observable to be present in a hard process. Because of the sign of the anomalous dimensions, the distribution vanishes asymptotically at a large resolution scale. The theoretically cleanest experiment is the Drell-Yan process with transversely polarized proton beams suggested by Ralston and Soper in 1979 [26]. A recent study by O. Martin et al. found a very small asymmetry at RHIC [28]. One can also measure it in inclusive jet production and direct photon production [29]. A recent estimate by Soffer at al. find an upper bound on the asymmetries at a level of 0.1 to 1 precent [30].

Another way to measure the transversity distribution is through chiral-odd quark fragmentation functions. The simplest example is the transversity fragmentation function, say, of a transversely polarized quark to a transversely polarized Lambda [31]. One can also couple it to the twist-two, time-reversal-odd fragmentation to two pions, for instance, the interference fragmentation between the s and p wave final states (see [32], [33], and [34]). There is also a twist-3 chiral-odd fragmentation function to pions [36]. Finally, there has been many discussions recently on a twist-2, time-reversal-odd, transverse-momentum dependent fragmentation to pion, the so-called Collins effects [35]. Unfortuately, these processes are not completely clean. In fact, quite often there are other competing processes contributing to the experimental observables.

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