Possible Polarization Dependence of Electromagnetic Current for Polarized Proton and Single-Spin Asymmetry in Lepton-Proton Scatterings

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Abstract

The polarization dependence of the electromagnetic vertex for polarized proton is proposed. Such a dependence is shown to be resulted from gluon polarization and gluon interactions with the constituents within proton. One more form factor is introduced to give such a dependence. Due the polarization dependence of the vertex, a nonzero single-spin asymmetry for unpolarized lepton scattering off transversely polarized proton is predicted.

PACS numbers: 13.60.Hb, 13.40.Gp, 13.60.F2

One of the most critical challenges facing the modern particle physicists is the understanding of nucleon structure. For a long time the theory of hadron structure remained comfortably at the level of the naive parton model, because a vast of unpolarized experimental data can be explained in that model. Experiments on polarized deep inelastic lepton-nucleon scattering started in the middle 70s [1]. In 1988, the EMC Collaboration measured the first moment of the proton spin structure function, $\Gamma_1^p \equiv \int_0^1 g_1^p(x)\,\mathrm{d}\,x$. The results [2] differed significantly from the naive theoretical predictions and known as EMC effect. The EMC effect motivated intensive further experimental and theoretical activities.

During the period of 1988-1993, theorists tried hard to resolve the proton spin enigma and seek explanation for the EMC effect, based on assuming the validity of the EMC data at small x ($0.01 < x < 0.1$) and of the extrapolation procedure to the unmeasured small x region ($x < 0.01$). The discussions on proton spin have been continuing up to now. Two successful first-principles calculations [3,4] of the quark spin contents based on lattice QCD were published last year. The calculations revealed that the sea-quark polarization arises from the disconnected insertion and is empirically SU(3)-flavor symmetric. This suggests that the conventional practice of decomposing Δq into valence and sea components is not complete, and the effect of "cloud" quarks should be taken into account. These calculations also show that the non-perturbative effects play an important role in spin phenomena. On the experimental side, deep-inelastic scattering experiments of polarized leptons off polarized nucleon were carried out recently at CERN [5] and SLAC [6]. The HERMES experiment will work at the ep collider HERA at DESY [7], which will give access to a so far unexplored kinematic region of lepton-nucleon scattering with rich physics potential. It is now well known that the physics of the polarized hadron-hadron interactions is very different from that of the unpolarized. 'Polarization data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection.' [8]. Indeed, the EMC effect on the spin dependent structure functions [2] has destroyed our naive expectations [9], and the role played by proton spin seems to be more important than that once assumed.

In this paper we come down to the very starting point of current theories for lepton-nucleon scatterings and try to seek whether there are some contents on the spin dependent effects not included in traditional theories yet. We study the elastic scattering of unpolarized lepton off polarized proton and seek for the parameterization for the electromagnetic vertex for proton. It is found that the traditional expression for the electromagnetic vertex for proton should be changed and an additional form factor should be introduced.

Consider elastic lepton scattering off proton. Denote m the lepton mass, k (k') the initial (final) lepton four-momentum and M the proton mass, P and S the initial proton four-momentum and spin four-vector. In current theories, the electromagnetic vertex for proton in elastic lepton-proton scatterings was assumed to be independent of the initial proton's spin orientation and was assumed to take a simple form as

$$J_\mu = e\bar{u}(P')\,\Gamma_\mu^{(\mathrm{trad})}\,u(P) \quad , \tag{1}$$

with

$$\Gamma_\mu^{(\mathrm{trad})} = F_1^{(\mathrm{trad})}(q^2)\gamma_\mu + \frac{\kappa}{2M}F_2^{(\mathrm{trad})}(q^2)i\sigma_{\mu\nu}q^\nu \quad , \tag{2}$$

and Dirac spinors $u(P)$ and $\bar{u}(P')$ are the same as those for free point-like particle with mass M, κ is the anomalous part of the magnetic moment in units of the Bohr magneton and scalar functions $F_1^{(\mathrm{trad})}$ and $F_2^{(\mathrm{trad})}$ are called form factors.

It is worthy to recall some facts: (i) The proton transition current of Eq.(1) was derived at a time when proton was regarded as elementary point-like particle; (ii) At that time the interaction between nucleons was regarded as a copy of electromagnetics, with massive π in place of massless photon; (iii) Spin effects were presumed at that time not so important as today, and one was usually satisfied with the spin averaged results; (iv) No polarized experiment was done in early years. Though theories based on Eqs. (1) and (2) can explain lots of unpolarized experiments, the validity of Eq. (2) for $\Gamma_\mu^{(\mathrm{trad})}$ in polarized processes had not been actually verified after the appearance of polarized lepton-nucleon experiments.

It is also fruitful here to recall that the transition current for proton (Eq. (1)) was assumed in current theory to be the same form as that for an electron in external electromagnetic field with quantum fluctuation considered. The only difference between them is that values of the form factors are different. It should be pointed out that the terminology 'form factor' implies not the compositeness of the considered particle but merely the existence of quantum fluctuation. So does the terminology 'structure function'. Now we know that proton is composed of quarks and gluons with interaction inside governed by the QCD. Thus it is clear that proton is very different from electron in: (i) Proton is a composite extended object while electron has no constituents; (ii) Interaction inside proton is mediated by exchanging colored gluons with nonabelian quantum fluctuations, while the quantum fluctuations for electron are mediated by the exchange of abelian photon. Keeping all those differences mentioned above in mind, one may ask why the electromagnetic current for proton should not take a different form from that for electron.

To answer this question let's investigate the photon interaction with polarized proton, taking into account the effects of strong interactions inside proton.

First of all, it is inevitable to accept the existence of hadronic current inside a polarized hadron as long as one accepts the concept of an extended hadron with a hadronic matter density in it, as pointed out in Ref. [10]. The hadronic current inside a polarized hadron can be understood when one notices that valence quarks inside hadron are relativistic Dirac particles moving in a confining field produced by other quarks. The orbital motion of such a relativistically moving Dirac particle is always involved – also when such particles are in ground states. Thus the orbiting quarks can induce the hadronic current. A particular feature of this hadronic current is that it depends on the polarization of the hadron. It is without any doubt that such a hadronic current in a polarized hadron will induce observable effects besides those mentioned in Ref. [10].

On the other hand, the gluon field inside a polarized hadron must also be polarized because this field is generated by the hadronic current which is dependent on the hadron polarization. This can be immediately seen from the classical Yang-Mills equation for strong interactions. Very recently, Ji [11] has obtained gauge-invariant expressions for the angular momenta for quarks and gluons inside a proton, both of which depend on proton's polarization, indicating quark's orbital motion and gluon's polarization. In fact, the polarization of gluons had been noticed several year ago [12] theoretically and experimental evidences [2] show that gluons might contribute almost total of proton's spin. Thus the net polarization of gluons should be along that of proton. Many authors have tried to account for the EMC effect in terms of anomalous gluon contribution [13-16].

Now one can evaluate the influence of the polarized gluon field on quark's wavefunction. From Dirac equation, the wavefunction of a quark inside polarized hadron can be formally written as

$$\Psi = \frac{1}{1-(\hat{p}-m)g\hat{B}}\,\Psi_0 \ , \tag{3}$$

where $\hat{A} \equiv \gamma^\mu A_\mu$, p the four momentum of the quark, B_μ is the gluon field acting on the quark, g is the coupling constant, Ψ_0 is Dirac spinor satisfying $(\hat{p}-m)\Psi_0 = 0$.

¿From the view point of field theory, the photon-quark interaction can be described by the Lagrangian

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{\rm strong} + \mathcal{L}_{\rm em} \ . \tag{4}$$

With this Lagrangian, one can prove that the transition current for the quark is [17]

$$J_\mu^q = e_q \overline{\Psi}(p', s')\,\Gamma_\mu^{(q)}\,\Psi(p, s) \quad , \tag{5}$$

with the form of $\Gamma_\mu^{(q)}$ the same as that given in Eq. (2). It must be emphasized that both $\Psi(p,s)$ and $\overline{\Psi}(p',s')$ in last equation are eigenstates of Hamiltonian $H_0 + H_{\rm strong}$, i.e., they are not free states of the quark but contain information about the gluon interactions inside polarized proton. One has seen from above discussions that B_μ depends on the polarization of proton, so that it is natural that the transition current for the quark inside polarized proton depends not only on the quark's spin s but on proton's polarization S. Last equation can be expressed in terms of states Ψ_0 as follows

$$J_\mu^q = e_q \overline{\Psi}_0(p', s')\,\Gamma_\mu^q(p, p', S)\,\Psi_0(p, s) \quad , \tag{6}$$

with Γ_μ^q depending on proton's polarization vector S.

The electromagnetic current of proton is the sum of those of quarks. Assuming the electromagnetic vertex for quarks is simply $e_q\gamma_\mu$, the electromagnetic vertex for elastic scattering between proton and photon should be of the form shown in Eq. (2). From above discussions, the vertex for photon-quark interaction depends on proton polarization, thus one has to admit that the vertex for proton-photon interaction should depend on the polarization S of initial proton. So the electromagnetic current for proton in elastic lepton-proton scattering is

$$J_\mu = e\overline{u}(P', S')\,\Gamma_\mu(P, P', S)\,u(P, S) \quad , \tag{7}$$

and Γ_μ should depend on proton polarization. Because of the never mentioned polarization dependence of Γ_μ, some modifications to the traditional expression for the electromagnetic vertex $\Gamma_\mu^{(\mathrm{trad})}$ for proton must be made. Physically it demands Lorentz covariance and current conservation, i.e. J_μ should be a true four-vector and satisfy $q^\mu J_\mu = 0$. The most general form of Γ_μ, which is composed of γ_μ, P_μ, q_μ and S_μ and makes all those physical restrictions satisfied, can be written as

$$\Gamma_\mu = F_1\gamma_\mu + \frac{F_2}{2M} i\sigma_{\mu\nu}q^\nu + \frac{F_3}{2M}\varepsilon_{\mu\nu\lambda\tau}\,\gamma^\nu S^\lambda q^\tau \quad , \tag{8}$$

where F_1, F_2 and F_3 are real functions of invariant variables q^2 and $(S\cdot q)^2$. The F_3 term represents the polarization dependence of proton structure, which can be attributed to the contribution of polarized gluons. Clearly, the additional term in last equation conserves the current and has proper parity because of the product of two pseudo-tensors $\varepsilon^{\mu\nu\lambda\tau}$ and S_λ. Furthermore, the additional term has the same properties as the first two terms under time-reversal transformation, which guarantees the T-invariance of the electromagnetic current for polarized proton.

Because of the polarization dependent term in the electromagnetic vertex for proton, new phenomena for elastic lepton-proton scatterings may exist. It is straightforward to show the symmetric part (or real part) of the hadronic tensor for proton to be as following

$$\begin{aligned} W^{\mu\nu}_{\mathrm{symm}} \;=\; & \left[8F_1^2 - 4F_2^2\left(1+\frac{q^2}{2M^2}\right]\right) + 2(F_1+F_2)^2 q^2\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right) \\ & + \frac{2F_3^2}{M^2}\varepsilon^{\mu\xi\eta\theta}\varepsilon^{\nu\rho\lambda\tau}S_\eta S_\lambda q_\theta q_\tau\left(P_\xi P_\rho + \frac{q^2}{4}g_{\xi\rho}\right) \\ & + \frac{4F_1F_3}{M}S_\lambda q_\tau P_\rho\left[\varepsilon^{\mu\rho\lambda\tau}\left(P^\nu - \frac{P\cdot q}{q^2}q^\nu\right) + \mu\leftrightarrow\nu\right] \ . \end{aligned} \tag{9}$$

Clearly, this hadronic tensor satisfies Eq. (42) in Ref. [18] and thus is T-invariant. When proton spin is reversed, terms in the first two lines will not change sign, but terms in the third sign will. If one considers unpolarized elastic lepton-proton scattering, terms in the third line contribute zero, and terms in the second line of last equation can be re-parameterized into the same forms as terms in the first line. Due to the presence of polarization dependent terms in the hadronic tensor for proton $W^{\mu\nu}_{\rm symm}$, one can predict a single-spin asymmetry for unpolarized lepton scattering off polarized proton. Let $L_{\mu\nu}$ be the lepton tensor in the process and S be the polarization of initial proton. If the initial proton is rest, the single-spin asymmetry can be expressed as

$$\begin{aligned} A &= \frac{\mathrm{d}\sigma(S)-\mathrm{d}\sigma(-S)}{\mathrm{d}\sigma(S)+\mathrm{d}\sigma(-S)} \\ &= \frac{16F_1F_3(k_0-q_0)\mathbf{k}\cdot(\mathbf{q}\times\mathbf{S})}{L_{\mu\nu}\left[W^{\mu\nu}_{\rm symm}(S)+W^{\mu\nu}_{\rm symm}(-S)\right]} \ . \end{aligned} \tag{10}$$

It is obvious that a zero value is obtained for the asymmetry A if the proton is longitudinally polarized. This result is not surprising because of the symmetric space about the polarization axis. Such an asymmetry is nonzero in the weak interactions because of parity and T-invariance violations in weak interactions was used many years ago to detect the weak interaction effects in the scatterings. Our result confirms that there exists no longitudinal polarization asymmetry for electromagnetic interactions because of P- and T invariances. For the case of transversely polarized proton, however, the asymmetric might exist. Similar asymmetry in hadron-hadron scatterings has been reported, which is very different from zero and larger than predicted from the perturbative QCD. In this paper, we predict the existence of nonzero asymmetry for the case of unpolarized lepton scattering off transversely polarized proton. We show that this asymmetry is caused due to the interactions with constitute quarks inside polarized proton of polarized gluon field. It is due to such interactions that the transverse momentum distribution of quarks inside proton depends on proton polarization whose effects on single-spin symmetry in DIS has just been investigated in Ref. [19].

Because of the polarization dependent term in the electromagnetic vertex for proton, new phenomena for deep inelastic lepton-proton scatterings may also exist.

Formally the polarized hadronic tensor $W_{\mu\nu}$ in deep inelastic scattering for N hadrons with energy and momemtum E'_n, P'_n, $(n=1,2,\cdots,N)$ in final state $\mid X\rangle$ can be written as

$$
\begin{aligned}
W_{\mu\nu} &= \frac{1}{4\pi M}\sum_N\int\prod_{n=1}^{N}\frac{d^3P'_n}{2E'_n(2\pi)^3}\langle p,s\mid\Gamma_\mu^{(V)\,\dagger}\mid X\rangle \\
&\quad \langle X\mid\Gamma_\nu^{(V)}\mid p,s\rangle(2\pi)^4\delta^4(p+q-\sum_{n=1}^{N}P'_n)\ . \qquad (11)
\end{aligned}
$$

Since Γ^μ depends on polarization, as shown above, the spin dependence of $W_{\mu\nu}$ comes from two ways: initial state spinor and transition current operator. Thus both the real part and the imaginary part in $W_{\mu\nu}$ depend on proton spin orientation. In the traditional theory, only the imaginary part in $W_{\mu\nu}$ depends on proton spin polarization, since the polarization dependence comes only implicitly through the initial state. Now, $W_{\mu\nu}$ should be constructed of q_μ, p_μ and s_μ together with other constant tensors. Under physical consideration the most general form of $W_{\mu\nu}$ can be written as

$$
W_{\mu\nu} = W_{\mu\nu}(\mathrm{S}) + iW_{\mu\nu}(\mathrm{A})\ , \qquad (12)
$$

with two terms of symmetric (S) and antisymmetric (A)

$$
\begin{aligned}
W_{\mu\nu}(\mathrm{S}) &= 2M\left(\frac{q_\mu q_\nu}{q^2}-g_{\mu\nu}\right)W_1+\frac{2}{M}\left(p_\mu-\frac{p\cdot q}{q^2}q_\mu\right)\left(p_\nu-\frac{p\cdot q}{q^2}q_\nu\right)W_2 \\
&+ \frac{2}{M^3}\varepsilon_{\mu\rho\lambda\tau}s^\rho p^\lambda q^\tau\varepsilon_{\nu\alpha\beta\eta}s^\alpha p^\beta q^\eta W_3 \\
&+ \left[\left(p_\mu-\frac{p\cdot q}{q^2}q_\mu\right)\varepsilon_{\nu\rho\lambda\tau}+\left(p_\nu-\frac{p\cdot q}{q^2}q_\nu\right)\varepsilon_{\mu\rho\lambda\tau}\right]s^\rho p^\lambda q^\tau\frac{W_4}{M^2}\ , \qquad (13) \\
W_{\mu\nu}(\mathrm{A}) &= \frac{2}{M}\varepsilon_{\mu\nu\lambda\tau}q^\lambda\left[s^\tau\left(MG_1+\frac{p\cdot q}{M}G_2\right)-p^\tau\frac{s\cdot q}{M}G_2\right]\ , \qquad (14)
\end{aligned}
$$

where $W_i(i=1,\cdots,4)$ and G_1, G_2 are real scalar functions of $q^2, p\cdot q$ and $(s\cdot q)^2$. One can show that the hadronic tensor for elastic lepton-proton scattering can be rewritten in the same forms as above. The two new structure functions W_3 and W_4 in the real part of $W_{\mu\nu}$ in Eq. (13) depend on the polarization of proton. The reason for Eq. (13) and (14) different from the traditional ones is that Γ^μ is taken as spin dependent. Thus one can predict a similar single-spin asymmetry,

$$
A = \frac{\mathrm{d}\sigma(\uparrow)-\mathrm{d}\sigma(\downarrow)}{\mathrm{d}\sigma(\uparrow)+\mathrm{d}\sigma(\downarrow)}\ ,
$$

where the arrows up and down denote proton spin up and down respectively.

Unfortunately no experimental data on asymmetry of single polarized lepton-proton scatterings are available yet, owing to the fact that all current theories predicted a zero result. To check the polarization dependence of the electromagnetic vertex for proton the measurement of single-spin asymmetry A defined above is necessary and sufficient which needs to be suggested at CERN and DESY. Recently the SMC collaboration has made a measurement of longitudinally polarized muons scattered from transversely polarized proton [5]. Their techniques can be used to test the single-spin asymmetry predicted in this paper.

Very recently, it is suggested [20] from chiral model for nucleon that the single-spin asymmetry may be produced from the dependence of transverse momentum in the distribution functions for quarks inside polarized proton. The transverse momentum distributions depend on proton's polarization and are not symmetric for $\mathbf{k} \longleftrightarrow -\mathbf{k}$ with given proton polarization. After summation over all quarks, the transverse momentum dependence should still exist unless there is unconceivable miracle of cancellation for the dependence. Then the polarization dependences of the proton transition current and the real part of hadronic tensor should exist.

As a summary we propose the polarization dependence of the electromagnetic, $\Gamma_\mu^{(V)}$, for proton in elastic lepton-proton scatterings. Our arguments are based on the consideration of the gluon polarization and its interactions with constituents within the proton. The polarization dependence of the vertex is given by a third form factor. The corresponding change for the hadronic tensor in deep-inelastic scatterings is also suggested, and two more structure functions are used to furnish the polarization dependence. Due to the new form factor and structure functions for polarized proton, there exists nonzero single-spin asymmetry for unpolarized lepton scattering from transversely polarized proton. Such an asymmetry needs to be verified experimentally.

If a confirmative result on single-spin asymmetry is really obtained from experiments, great changes will happen in both theoretical and experimental studies of elastic and deep inelastic scattering processes.

This work was supported in part by the NNSF and the SECF in China. The authors thank Prof. T. Meng for helpful discussions.

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