Spin effects and rotating color charges in proton-proton elastic scattering

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It is suggested that the nonzero analyzing power A observed in large-$p_\perp^2$ elastic $pp(\uparrow)$ scattering is an indication for the existence of rotating color charges in polarized protons. Such color charges induce color-magnetic fields and thus give rise to an additional, velocity-dependent, interaction. The effects of this interaction are discussed phenomenologically at the hadronic level.

Since the publication of the European Muon Collaboration spin-asymmetry measurements[1] which triggered the "spin crisis,"[2] there has been much discussion[2] on the possible origin of the proton's spin. In particular, the old question[3] "Can the spin of a hadron be attributed to the orbital motion of its constituents?" has received much attention.[2,4] Experiments have been proposed,[5] the aim of which is to answer this question *directly*. While waiting for the results expected in the future,[6] we looked, in the *presently available* polarization data, for evidence *for or against* the idea of rotating hadronic matter in polarized protons. The present paper is a short report on this attempt.

It is well known that the conceptually simplest polarization phenomenon is the following observation[7–9] made in elastic proton-proton scattering. The spin-analyzing power A was measured in a series of experiments[8,9] at incident momentum $p_{\text{lab}}=28$ GeV/c, using polarized targets and unpolarized beams. The $p_\perp^2$ (the transverse momentum of the scattered proton) ranges from 2.85 to 6.5 (GeV/c)^2. It is seen that A is very much different from zero for $p_\perp^2>4$ (GeV/c)^2. In fact, A increases dramatically in this region, and reaches $(24\pm8)\%$ at $p_\perp^2=6.5$ (GeV/c)^2. We recall that the analyzing power A is defined as

$$A=-\frac{1}{|P_T|}\frac{N(\uparrow)-N(\downarrow)}{N(\uparrow)+N(\downarrow)} \tag{1}$$

and it was obtained from the measurements of the normalized event rates $N(i)$ ($i=\uparrow$ or $\downarrow$) of the transversely polarized target. Here, P_T is the target polarization; and the Basel convention was used in the definition of A (and thus the minus sign occurs because the forward proton in this experiment scatters to the right).[8,9] Since perturbative QCD yields $A=0$, these "very nonzero values"[7] have been considered as one of the most striking results—if not *the* most striking result—obtained in polarization experiments.

In order to see the implication of these experimental results and to study their (possible) relationship to rotating constituents, it seems useful to recall the following (well-known) facts. First, hadrons are spatially extended objects, and hadronic interactions are short ranged. A collision process between two hadrons (P and T, say) takes place only when they are so close to each other that the constituents of P interact with those of T. For the description of such collisions, it is convenient to use the notion of an an impact parameter b defined with respect to the centers of P and T. Hence b is a measure of the degree of overlap of the two systems, and large momentum-transfer processes are associated with relatively small b values. Second, rotational motion of the constituents inside polarized hadrons implies the existence of axial-symmetric currents of hadronic matter.[3] We are thus led to the following question: Can such currents effect the relevant hadronic interaction and yield observable effects in large-momentum-transfer collisions at high and/or intermediate energies?

We argue that such effects are expected to exist if the constituents of hadrons are identified as (spin-$\frac{1}{2}$) quarks/antiquarks and (spin-1) gluons carrying color charges. In doing so, we make use of the fact that the gauge principle is valid in nature, and that the similarities and differences between the two relevant gauge groups, U(1) and SU(3), play an important role.

Let us first consider the hadronic constituents as if they were simply electric charges. That is, we first consider a system T of electric charges symmetrically distributed with respect to a given point T_0 say. We choose a right-handed Cartesian coordinate in the laboratory such that the origin is fixed at T_0, and compare the following two cases: Case 0 in which all the charges are at rest, case $\uparrow$ in which the charges are rotating counterclockwise about the x axis. The angular velocities of the charges are in general different, such that there is a distribution of local angular velocity of these charges. Since moving electric charges are nothing else but electric currents which generate magnetic fields, the behavior of another charge (or another system of charges having the same e/m, charge/mass, ratio, represented by a single point) P moving in the yz plane in case 0, and that in case $\uparrow$ are obviously different from each other. This is because in the latter case magnetic fields are induced by the rotating charges. To be more precise, the induced magnetic field strength $\mathbf{B}$ is in the x direction, and it can approximately be considered as uniform and constant in a given domain in T. Hence, it is convenient to use Lamor's theorem[10] and its straightforward generalization to describe the motion of P. In the above-mentioned laboratory frame, P experiences an additional force, because it is moving (with velocity $\boldsymbol{\beta}$, say) in the magnetic field $\mathbf{B}$ induced by the rotating charges in T. The force is proportional to the vector product of $\mathbf{B}$ and $\boldsymbol{\beta}$ and thus it is also in the yz plane. Furthermore, this force is equivalent to the apparent force—Coriolis force—on P, viewed from a rotating reference frame, provided that the angular velocity $\boldsymbol{\Omega}$ of the rotating frame and the induced magnetic field strength $\mathbf{B}$ are parallel and proportional to each other (in the limiting case we have the well-known result $\boldsymbol{\Omega}=e\mathbf{B}/2mc$. We note that although $\mathbf{B}$ can be calculated in a straightforward way [if the charge density $\rho(\mathbf{r})$ and the distribution of angular velocity of the charges $\boldsymbol{\omega}(\mathbf{r})$ are explicitly known] it is simpler to use Larmor's theorem and describe the effects caused by the rotating electric charges in terms of the corresponding quantity $\boldsymbol{\Omega}$ where $\boldsymbol{\Omega}$ is proportional to $\boldsymbol{\omega}$, the averaged value of $\boldsymbol{\omega}(\mathbf{r})$ for a given domain in T.

Next, we ask the following. "What happens if we make the following replacement in this consideration: electric charge$\rightarrow$color charge, photon field$\rightarrow$gluon field?"

We adopt the conventional picture[11] described by the (improved) bag model and QCD (to the order to which gluon self-coupling can be neglected). In this picture the gluons act as if they were eight independent Abelian fields and the problem here is analogous to one of conventional electromagnetism in a cavity. That is, rotating color charges inside a polarized hadron can be considered as color currents which induce color-magnetic fields; and in particular, in a given domain inside the hadron, such color-magnetic field strength can approximately be considered as uniform and constant. This basic characteristic property of QCD is taken into account as follows. Because of confinement, quark and gluon fields can never cross the boundary in which the color charges are distributed. This implies in particular that, inside the system T, the sign of $\mathbf{B}(r)$ and that of $\boldsymbol{\omega}(r)$, which are, respectively, the induced color-magnetic field strength and the average angular velocity of the rotating color charges at distance r from the polarization axis, *cannot* always be the same. On adopting the usual picture[12] in which the force between two nucleons at very small impact parameters is repulsive, and on applying again the Larmor theorem[10] and its generalization we are led to the following conclusions: The effective additional force $\mathbf{f}^{\mathrm{RC}}$ acting on the system P in the laboratory frame, caused by the rotating color charges of the polarized proton in a given (rather large) range of impact parameters, has the form

$$\mathbf{f}^{\mathrm{RC}}=\lambda\boldsymbol{\omega}\times\boldsymbol{\beta} \; . \tag{2}$$

Here, $\boldsymbol{\omega}$ is the average value of $\boldsymbol{\omega}(\mathbf{r})$ (the distribution of the local angular velocity of the color charges in the target proton in a given range of impact parameters), $\boldsymbol{\beta}$ is the velocity (in units of c) of the projectile proton, and λ is a positive constant. The following remarks should be made in connection with $\mathbf{f}^{\mathrm{RC}}$. First, because of its "magnetic origin," $\mathbf{f}^{\mathrm{RC}}$ depends on $\boldsymbol{\beta}$. (The simplest way to see this is to write the Lorentz-force equation in the covariant form. See, e.g., Ref. 13.) Since β is approximately unity at sufficiently high incident energies, $\mathbf{f}^{\mathrm{RC}}$ depends very little on the incident momentum. Second, $\mathbf{f}^{\mathrm{RC}}$ can be interpreted as a special kind of effective "spin-orbit interaction"[14] caused by the "interquark spin-orbit interactions." (Compare the relevant interaction terms in the Lagrangian for the quarks and the corresponding term in the *effective* Lagrangian at the hadronic level, and obtain the *effective force* $\mathbf{f}^{\mathrm{RC}}$ from the latter.) Furthermore, it is interesting to note the similarity between this interaction and the nuclear "Coriolis interaction."[15]

We now compare our result with the experimental findings.[7-9] In order to show the essential points of the proposed reaction mechanism, it is our intention to make the comparison as "anschaulich" (clear, plain, evident, perceptual) as possible. Fortunately enough, concepts and methods of classical physics are applicable here. We recall that, for a classical treatment of particle scattering to hold, the orbit and the deflection should be well defined in relation with the dimension of the interaction.[16] That is, for a scattering field extending over a dimension of the order ξ, the scattering of particles with initial momentum p, momentum transfer Δp can be described classically when the inequalities $\xi p \gg 1$, $\xi\Delta p \gg 1$ are satisfied ($c=\hbar=1$). Hence, classical concepts and methods should be useful for high-energy, large-momentum-transfer hadron-hadron collision processes such as those dealt in this paper. In particular, the differential cross section $d\sigma/dp_\perp^2$ is simply proportional to $b\,db$, where b is the impact parameter. That is,

$$\frac{d\sigma}{dp_\perp^2} \propto b\left[\frac{dp_\perp^2}{db}\right]^{-1} . \tag{3}$$

We neglected all the other (energy- and $p_\perp$-dependent) factors in Eq. (3), because they will be canceled when we insert the corresponding expressions for $d\sigma/dp_\perp^2$ into Eq. (1) to calculate A.

We compare the results obtained in the following three cases. Case 0: The target-proton is unpolarized. Case $\uparrow$: The target-proton is polarized transverse to the scattering plane in which the projectile is scattered to the right of the beam axis. Case $\downarrow$: The polarization of the target-proton in case $\uparrow$ is reversed.

In the laboratory system in which the origin is fixed to the center of the target proton, the x axis perpendicular to the scattering plane, and the incident proton is moving in the z direction, the effective additional force $\mathbf{f}^{\mathrm{RC}}$ in case $\uparrow$ is, according to Eq. (2), in the negative y direction. That is, compared to case 0, the projectile in case $\uparrow$ "gets an extra pull" when it passes the target proton on its right-hand side, and it would "obtain an extra push" when it passes the target proton on its left-hand side. Furthermore, it is obvious that $\mathbf{f}^{\mathrm{RC}}$ changes sign and thus right/left and pull/push will be reversed, when the target proton is polarized in the opposite direction (see case $\downarrow$ mentioned above).

We recall that at the hadronic level, large-angle elastic scattering at high energies is due to strong repulsive interactions. The strength of such a repulsive force increases with decreasing impact parameter. The additional force $\mathbf{f}^{\mathrm{RC}}$ causes a change in the effective force, and thus a change in the effective impulse on the scattered projectile. Hence, for the projectile proton *to obtain the same momentum transfer* from a polarized target (case ↑ or ↓) as it would obtain from an unpolarized one (case 0), *the values of the impact parameter in these three cases are in general different from one another.* Taking the value in case 0 as reference, there is a shift in impact parameter in case ↑, and a shift in case ↓. For a given static hadronic central force the *shift in impact parameter* due to the additional force depends not only on the direction of the polarization, but also on the velocity and the position of the projectile with respect to the target. This point is illustrated in Fig. 1.

We note that in the BNL Alternating Gradient Synchrotron (AGS) experiments,[8,9] in which the analyzing power A has been measured, the forward proton spectrometer F is on the right-hand side of the target. We also note, in our interpretation, that the forward proton is identified as the scattered projectile, and that large-angle scattering is due to the hadronic force between the colliding protons. Hence, in this picture, every observed event in the AGS experiments[7-9] is an elastic scattering event in which the projectile proton hits the right-hand side of the target proton. This means that, in case ↑, the impact parameter $b_\uparrow$ has to be smaller than the corresponding impact parameter b in case 0 if the effective momentum transfer (and thus the transverse mometum of the scattered proton) are the same. Similarly, in case ↓, the impact parameter $b_\downarrow$ has to be larger than b. Therefore, the analyzing power A, as defined in Eq. (1) *should be positive for sufficiently large* $p_\perp^2$, *and should increases for increasing* $p_\perp^2$ (note that b decreases while the repulsive nuclear force increases for increasing $p_\perp^2$). In order to obtain a quantitative estimate, let us, for the sake of simplicity, assume that the magnitude of the shift in case ↑ and that in case ↓ are approximately the same. Denoting the increment by $\Delta b^{\mathrm{RC}}>0$, we immediately obtain, from Eqs. (1) and (3),

$$A \approx \frac{\Delta b^{\mathrm{RC}}}{b} . \tag{4}$$

Here, we explicitly see how A changes with the impact parameter. Taken together with the relationship between $p_\perp$ and b (cf. Fig. 1) we also see how it changes with the transverse momentum.

In summary, the proposed model agrees well with the experimental findings.[2,7-9] In this model, *A is nonzero;* in fact, *A is positive for sufficiently large values of* $p_\perp^2$. Furthermore it has the following features. First, since it is $\boldsymbol{\beta}$ (the magnitude of which is approximately equal to 1 for sufficiently high energies) that appears in $\mathbf{f}^{\mathrm{RC}}$, *the analyzing power A is expected to depend very little on the incident energy.* Second, Δb^{RC} is approximately constant, and the corresponding values for the impact parameter b are small for large values of momentum transfer. Hence, according to Eq. (4) *A is expected to increase for increasing* $p_\perp^2$. [Because of the constraint $A(\theta=90°)=0$, where θ is the scattering angle in c.m. frame, this increase with $p_\perp^2$ at a given incident energy can of course not continue indefinitely. It drops very fast near $\theta=90°$ where the identical particle effect becomes significant. For details, see Ref. 17.] Note that all these properties are independent of the undetermined parameters, and hence they are basic characteristics of the proposed model. It would be interesting to see whether these properties—and thus the proposed model—can stand future experimental tests. As a next step, we are now performing a relativistic quantum-mechanical calculation,[17] at the hadronic level, for this and for other measurable quantities[2,7] in elastic proton-proton scattering processes.

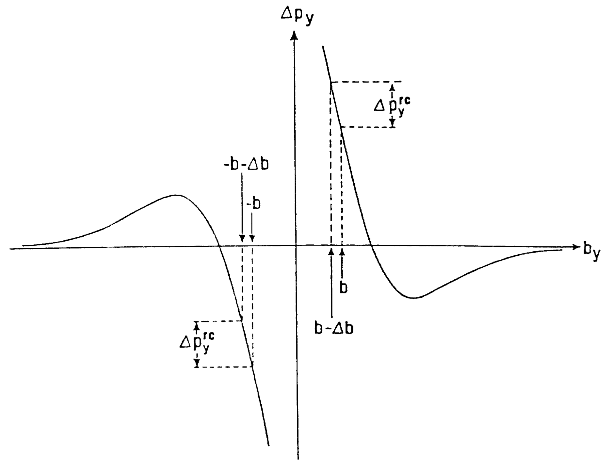

FIG. 1. The dependence of transverse-momentum transfer on impact parameter. This qualitative relationship is obtained under the condition that a central short-range repulsive force and a central relatively long-range attractive force can be used to account for the hadronic force between the nucleons. Here, b_y is the y component of the two-dimensional impact parameter (b_x,b_y). Δp_y is the momentum transfer in the y direction. The superscript RC in Δp_y^{RC} indicates the part of Δp_y due to the additional effective iteraction caused by the rotating color current.

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[11]See, for example, F. Close, *Introduction to Quarks and Partons* (Academic, London/New York/San Francisco, 1979), p. 421.

[12]Consistent with the conventional picture for hadron structure [see, for example, K. Gottfied and V. Weisskopf, *Concepts of Particle Physics* (Oxford University Press, New York, 1986), Vol. II, p. 401], it is envisaged that the lines of the magnetic field strengh **B** is parallel to $\boldsymbol{\omega}$ at very short distances ($r \ll r_0$) and antiparallel elsewhere, and $|\mathbf{B}| \rightarrow 0$ as $r \rightarrow r_0$ (r_0 is of the order of hadron radius).

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[14]We recall that "spin-orbit"-type interactions have been used already in the 1950s [see E. Fermi, Nuovo Cimento **11**, 407 (1954); G. A. Snow, R. M. Sternheimer, and C. N. Yang, Phys. Rev. **94**, 4 (1954)] to describe polarization effects observed in elastically scattered nucleons from nuclei. In these papers, the "nuclear spin-orbit interaction potentials" were taken to be similar to that assumed in the nuclear shell model. The effect of spin-orbit-type interactions on polarization in hadron-hadron collisions has been discussed by L. Durand and F. Halzen [Nucl. Phys. **B104**, 317 (1976); Phys. Rev. D **15**, 352 (1977)]. No comments were made on the possible origin or energy dependence of these interactions.

[15]See, e.g., A. Bohr and B. Mottelson, *Nuclear Structure* (Addison-Wesley, Reading, MA, 1975), Vol. II, p. 145, and the references given therein.

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[17]Such an additional interaction reproduces polarization effects in classical as well as in quantum-mechanical calculations. See Cai Xu, Meng Ta-chung, Zhou Zhi-ning and Zhou Zhuo-mei FU report (in preparation).