Impact-picture description of high-energy elastic proton-proton polarization

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A model of rotating matter inside the proton was recently proposed to explain low- and high-energy proton-proton elastic scattering. Predictions made for the polarization at high energy and recent experiments at CERN and Fermilab support this concept of matter current inside a hadron.

High-energy experiments performed in the past at CERN ISR and Fermilab have proven to be of great interest in hadron physics for spin-independent cross sections. Although the behavior of the proton-proton cross section was guessed on the theoretical level, the new experimental results have brought more precise information on the most difficult particle exchange to understand, namely, the Pomeron. It was also expected that at high energy where the Regge background becomes negligible, the spin observables would vanish, and as a consequence one would not care about helicity-flip amplitudes associated with the pomeron.

Recently, experiments on p-p elastic scattering at CERN SPS (Ref. 1) and Fermilab (Refs. 2 and 3) have revealed that polarization persists at energies up to 300 GeV/c. The present range of momentum transfer (up to 3 GeV^2) for these experiments corresponds to small-angle scattering. If measurements at larger angles were available, one might observe as much structure as that seen at medium energy.[4] Elastic scattering is not the only domain where spin effects have been observed at high energy. The inclusive reactions provide even more striking results; the production of polarized hyperons shows important asymmetries in a range of energy including ISR.[5]

Very few theoretical attempts[6] exist to interpret these elastic data; this is mainly due to the difficulty to understand the nature of the Pomeron helicity flip. Two years ago, some of us proposed[7] to describe proton-proton elastic scattering in a way compatible with the results of quantum field theory, namely, by including s-channel unitarity, t-channel unitarity, analyticity, and crossing symmetry. The spin dependence of the proton amplitude results from a simple physical picture of rotation of matter inside the proton; this concept of matter current inside a proton is due to Chou and Yang.[8]

Results on total cross section, differential cross section, polarization, and R parameter agreed well with the existing data at the time, so in view of future experiments some predictions on observables were made,[7] in particular, on polarization.

These predictions are also in good agreement with the recent data of the CERN SPS (Ref. 1) and Fermilab (Refs. 2 and 3). In this paper we would like to report on these results and emphasize the validity of the concept of hadronic matter current.

In order to explain these results we summarize the main features of the model, for which a complete development is given in Ref. 7. The proton-proton elastic amplitude in impact-parameter representation reads as

$$M(s,t)=\frac{is}{2\pi}\int e^{-i\vec{q}\cdot\vec{b}}(1-e^{-\Omega(s,\vec{b})})d\vec{b}\ , \quad (1)$$

where $\vec{q}$ is the momentum transfer ($t=-\vec{q}^{\,2}$), and $\Omega(s,\vec{b})$ is defined to be the opaqueness at impact parameter $\vec{b}$ and at a given energy s. The total opaqueness $\Omega(s,\vec{b})$ is decomposed into a spin-independent part $\Omega_0(s,\vec{b})$ and a spin-dependent part $\Omega_1(s,\vec{b})$ such that

$$\Omega(s,\vec{b})=\Omega_0(s,\vec{b}^{\,2})\mp\Omega_1(s,\vec{b}^{\,2})\hat{b}_x\ , \quad (2)$$

where $\mp$ refer to a target spin $\pm\frac{1}{2}$ along the z axis; $\hat{b}_x$ is a component of a unit vector $\hat{b}=\vec{b}/|\vec{b}|$.

(i) The spin-independent part is itself defined as the sum of two terms:

$$\Omega_0(s,\vec{b}^2)=S_0(s)F(\vec{b}^2)+R_0(s,\vec{b}^2) \quad ; \tag{3}$$

the first term is associated with the "Pomeron" exchange, while the second term, whose exact expression can be found in Ref. 7, is a Regge background which becomes negligible at high energy. The function $S_0(s)$ comes from the high-energy behavior of quantum field theory,[9] and we shall take the crossing-symmetric expression

$$S_0(s)=\frac{s^c}{(\ln s)^{c'}}+\frac{u^c}{(\ln u)^{c'}} \quad . \tag{4}$$

The dependence upon the impact parameter is contained in the function $F(\vec{b}^2)$, whose Fourier transform is proportional to the square of an approximate parametrization of the proton form factor

$$\tilde{F}(t)=f\left[\frac{1}{(1-t/m_1^2)(1-t/m_2^2)}\right]^2\frac{a^2+t}{a^2-t} \quad . \tag{5}$$

All the parameters have been adjusted by fitting the $\bar{p}$-p total-cross-section data and the elastic p-p data on σ_{tot}, $\rho=\text{Re}a_0/\text{Im}a_0$, and $d\sigma/dt$; they have the following values:

$$\begin{aligned}&c=0.151,\quad c'=0.756\quad ,\\ &m_1=0.619\text{ GeV},\quad m_2=1.587\text{ GeV}\quad ,\\ &a=2.257\text{ GeV},\quad f=8.125\quad .\end{aligned} \tag{6}$$

This is all that is needed to calculate the spin-independent amplitude:

$$a_0(s,t)=is\int_0^\infty J_0(b\sqrt{-t})(1-e^{-\Omega_0(s,\vec{b}^2)})b\,db \quad . \tag{7}$$

(ii) The spin dependence of the amplitude originates from the idea that the matter inside a proton is subject to a movement due to the presence of a current. This concept of matter current inside a polarized hadron was first proposed by Chou and Yang,[8] and complements nicely the notion of hadronic matter density. These two concepts result from the analogy with the electromagnetic charge and current densities. We are fully aware that the analogy is not exact; however, it has been proven to be of interest when describing the p-p elastic $d\sigma/dt$, and as we shall see below for the polarization.

We suppose that the collision between two protons occurs in the x-y plane, and the direction of the incident proton is along the y axis. Let us call v_y the y component of the velocity of a small region of the target in the c.m. system. The effective energy of the projectile in the rest-system region of the target is in the first order:

$$s_{\text{eff}}=s(1-v_y) \quad . \tag{8}$$

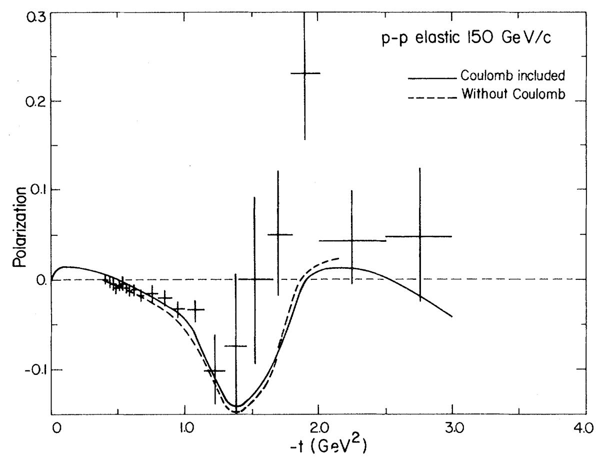

FIG. 1. Elastic proton polarization at $p_{\text{lab}}=150$ GeV/c (data from Ref. 1). The curve is a prediction of the soft-rotation model.

Taking into account s_{eff}, the energy dependence of the Pomeron exchange is modified according to

$$\begin{aligned}&S_0(s)\rightarrow S(s,\vec{b})=S_0(s_{\text{eff}})\sim S_0(s)-sv_y\frac{\partial}{\partial y}S_0(s)\quad ,\\ &S(s,\vec{b})=S_0(s)-v_yS_1(s)\quad ,\end{aligned} \tag{9}$$

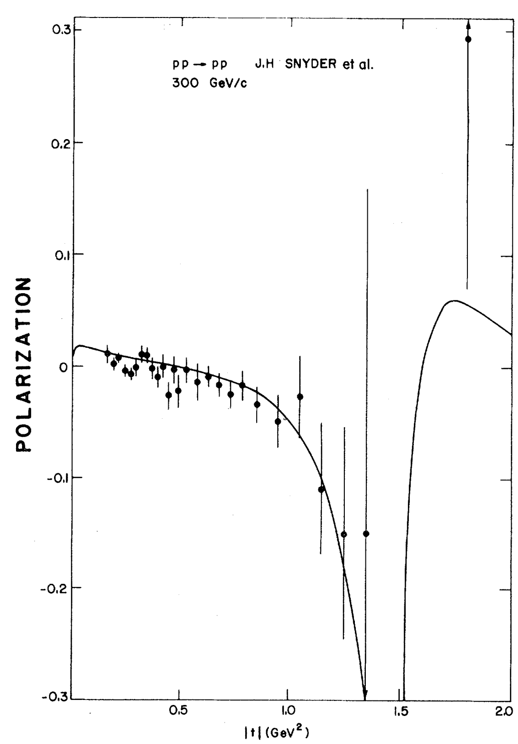

FIG. 2. Elastic proton polarization at $p_{\text{lab}}=300$ GeV/c (data from Ref. 3). The curve is a prediction of the soft-rotation model.

with

$$S_1(s)=\frac{s^c}{(\ln s)^{c'}}\left[c-\frac{c'}{\ln s}\right]+\frac{u^c}{(\ln u)^{c'}}\left[c-\frac{c'}{\ln u}\right] \ . \tag{10}$$

If we set

$$v_y=\omega(b^2)\,\hat{b}_x b \ , \tag{11}$$

we get

$$\Omega_1(s,\vec{b}^2)=F_s(\vec{b}^2)S_1(s)+R_1(s,b) \ , \tag{12}$$

$$F_s(\vec{b}^2)=b\,\omega(b^2)F(\vec{b}^2) \ , \tag{13}$$

where $F(b^2)$ is the Fourier transform of Eq. (5), $\omega(b^2)$ is an unknown function for the moment, and $R_1(s,b)$ is a spin-dependent Regge background. Inserting Eq. (12) into Eq. (2), the total amplitude defined by Eq. (1) takes the form

$$M(s,t)=a_0(s,t)+i\,\vec{\sigma}\cdot\vec{n}\,a_1(s,t) \ , \tag{14}$$

$\vec{n}$ being a unit vector normal to the scattering plane and $a_1(s,t)$ the spin-dependent amplitude:

$$a_1(s,t)=is\int_0^\infty J_1(b\sqrt{-t}\,)\,\Omega_1(s,\vec{b}^2)\,e^{-\Omega_0(s,\vec{b}^2)}\,b\,db \ . \tag{15}$$

Once the function $\omega(b^2)$ is specified, we are able to calculate the polarization P in the laboratory system produced by the scattering of a proton on a polarized

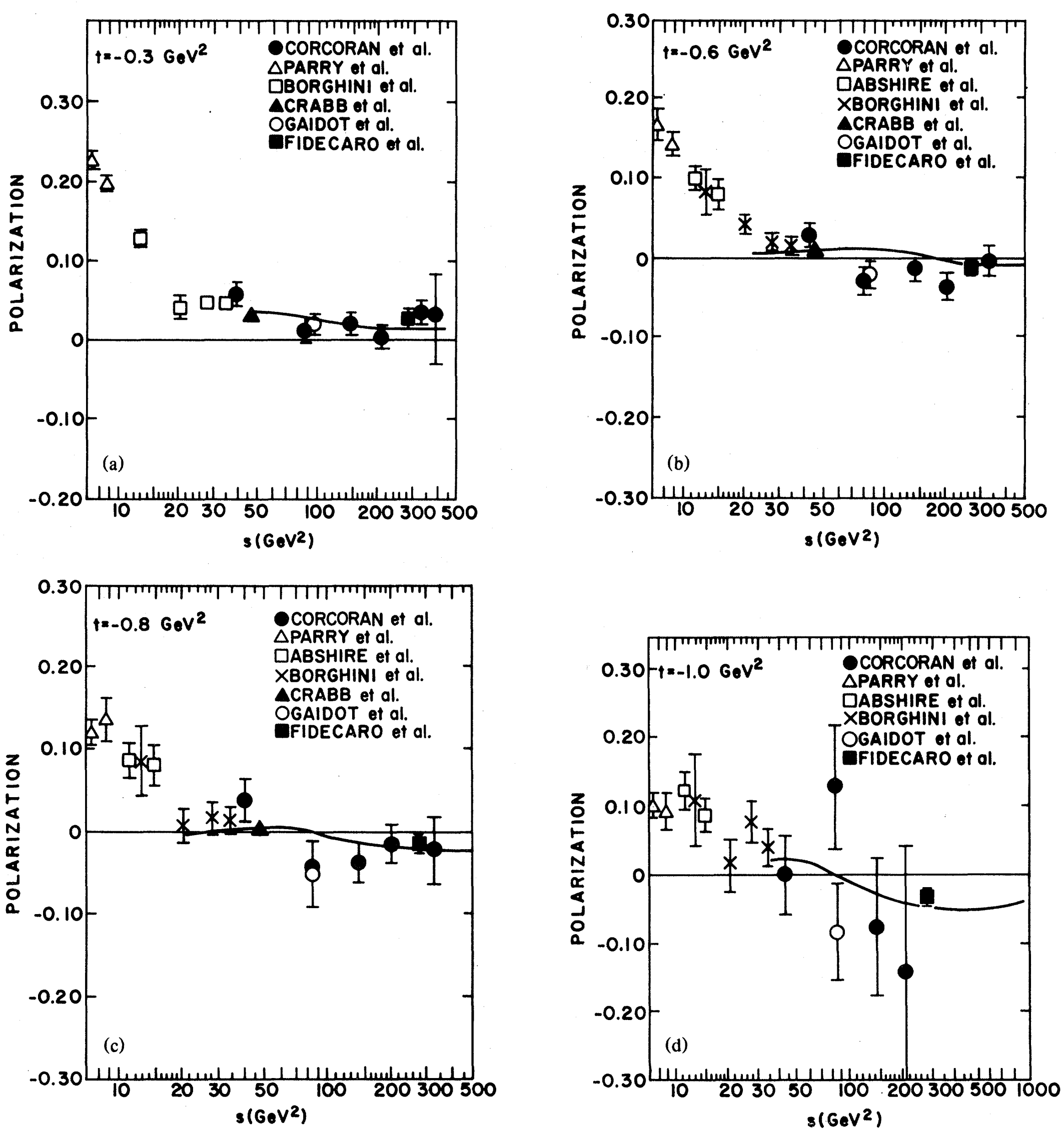

FIG. 3. Elastic proton polarization as a function of s for different t values (data from Refs. 1, 2, and 10). The curves are a prediction of the soft-rotation model.

target.

$$\sigma_0 P = 2\,\mathrm{Im}(a_0 a_1^*) \quad , \quad \sigma_0 = |a_0|^2 + |a_1|^2 \ . \tag{16}$$

The hadronic matter velocity inside a proton defined by Eq. (11) cannot be estimated on a purely theoretical basis. So as a first guess we choose to take the simplest assumption $\omega(b^2) = \omega = \text{const}$, which corresponds to a *rigid rotation* of angular velocity ω. This assumption, which was already ruled out by theoretical arguments,[7] disagrees anyway with recent data.[1,2]

We find more suitable to assume that $\omega(\vec{b}^2) \to 0$ when $\vec{b}^2 \to \infty$, such matter motion will be referred to as *soft rotation.* Our present theoretical knowledge does not allow a precise determination of the function $\omega(\vec{b}^2)$, therefore we choose arbitrarily a Gaussian form

$$\omega(b^2) = \omega_0 e^{-\vec{b}^2/b_0^2} \ . \tag{17}$$

The fit of low-energy data between 17 and 100 GeV/c shows that the value of the parameters are $\omega_0 = -0.06$ GeV, $b_0 = 3.75\ \mathrm{GeV}^{-1}$. Our predicted values of the polarization above 100 GeV/c are displayed on Fig. 1 for the CERN experiment[1] at 150 GeV/c, and on Fig. 2 for the Fermilab data at 300 GeV/c. On Fig. 3 we show the comparison of the model with the results of different experiments[10] including new Fermilab data[2] with different bins of momentum transfer.[11]

Coulomb amplitudes in one-photon-exchange approximation are included in the calculation of the polarization.[12] We would like to stress that Coulomb interference is generally believed to be important only at very small momentum transfer and negligible for larger values. This is certainly true when the measured polarization is large; however, at high energy for $t < 1\ \mathrm{GeV}^2$, where the polarization is of the order of a few percent, Coulomb interference cannot be neglected in interpreting the data.[13]

The good agreement of our curves with these recent data supports the concept of matter current inside a hadron and indicates that the picture of soft matter rotation in a proton is realistic. We expect further confirmation when measurements of the R parameter, whose predictions are given in Ref. 7, will become available.

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[11]In Ref. 2 (curve c of Figs. 12–15), the comparison of the results of Ref. 7 was not correctly transcribed.
[12]The fact that both the Coulomb effect and the hadronic effect contribute to the calculation of the polarization is not clearly stated in Ref. 2, Sec. V A 3.
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