Energy Dependence of the Pomeron Spin-Flip

B.Z. Kopeliovich\textsuperscript{1,2} and B. Povh\textsuperscript{2}
\textsuperscript{1} Max-Planck-Institut für Kernphysik
Postfach 30980, 69029 Heidelberg, Germany
\textsuperscript{2} Joint Institute for Nuclear Research
141980 Moscow Region, Dubna, Russia

There is no theoretical reason to think that the spin-flip component of the Pomeron is zero. One can measure the spin-flip part using Coulomb-nuclear interference (CNI). Perturbative QCD calculations show that the spin-flip component is sensitive to the smallest quark separation in the proton, while the non-flip part probes the largest separation. According to HERA results on the proton structure function at very low $x$ the energy dependence of the cross-section correlates with the size of the color dipole. Analysing the data from HERA we predict that the ratio of the spin-flip to non-flip amplitude grows with energy as $r(s) \propto (1/x)^{0.1-0.2}$, violating Regge factorization of the Pomeron.

How to measure the Pomeron spin-flip?

The Pomeron contribution to the elastic scattering amplitude of a spin $1/2$ particle has a form

$$f^P(s, t) = f^P_\text{flip}(s, t) \left[ 1 + i \frac{\sqrt{-t}}{m_N} \vec{n} \cdot \vec{r}(s, t) \right]$$

(1)

The function $r(s, t)$ characterises the Pomeron spin-flip to non-flip ratio. In the case of $NN$ elastic scattering $r$ can be expressed through the spin amplitude in standard notations

$$r = \frac{2m_N}{\sqrt{-t}} \frac{\Phi_5}{\text{Im}(\Phi_1 + \Phi_3)}$$

(2)

If the Pomeron is a Regge pole (factorization holds), the spin-flip and non-flip amplitudes have the same phase, i.e. $r$ is pure imaginary. Either this is true, or Re $r \ll 1$. Indeed, a real part of $r$ would lead to a polarisation in the elastic amplitude due to ”self-interference” of the two components of the Pomeron,

$$A_N^{pp}(t) = \frac{\sqrt{-t}}{m_N} \frac{4\text{Re } r(t)}{1 + |r|^2 |t|/m_N^2},$$

(3)

which is measured to be less than 1% at high energies. On the other hand, even if $|r|$ is quite large, the polarisation may be small provided that factorization
approximately holds. As soon as the polarisation is insensitive to the Pomeron spin-flip, it makes it difficult to measure \( r \) in elastic hadronic scattering.

A unique way to measure \( r \) is to study the polarisation effects due to interference of electromagnetic and hadronic amplitudes (CNI - Coulomb-Nuclear Interference). The corresponding polarisation in \( pp \) elastic scattering reads:

\[
A_N^{pp}(s, t) = A_N^{pp}(t_p) \frac{4y^2}{3y^2 + 1},
\]

where \( y = |t|/t_p \),

\[
t_p(s) = \frac{8\pi \sqrt{3\alpha_{em}}}{\sigma_{tot}},
\]

and

\[
A_N^{pp}(t_p) = \frac{\sqrt{3}t_p}{4m_p}(\mu - 1).
\]

Here \( \mu - 1 = 1.79 \) is the anomalous magnetic moment of the proton.

It was assumed in that \( \text{Im } r = 0 \), otherwise one should replace

\[
(\mu - 1) \Rightarrow (\mu - 1) - 2\text{Im } r
\]

This provides a parallel shift of the function (4) up or down dependent on the sign of \( \text{Im } r \). Therefore, measurement of \( A_N \) in the CNI region seems to be a perfect way to study \( r \). First very crude measurements were performed by the E704 Collaboration at Fermilab with 200 GeV polarised proton beam. The results are in a very good agreement with the predictions (4)-(6), but can be also used to establish soft bounds on the possible value of \( \text{Im } r \). According to the analyses, the data demand

\[
\text{Im } r < 0.15 \pm 0.2
\]

Much more precise measurements are expected to be done with polarised proton beams at RHIC.

Another available source of information about the Pomeron spin-flip is the data on polarisation in \( \pi^\pm p \) elastic scattering, which have a reasonable accuracy at energies 6 - 14 GeV. The dominant contribution of the \( \rho \)-Reggeon and Pomeron interference cancels in the sum of the polarisations. The rest is due to Pomeron and \( f \)-Reggeon interference. Its value can be used for an upper bound on the Pomeron spin-flip (assuming that \( f \) has no spin-flip), which was found to be less than 3%.

Theoretical attempts to estimate the value of \( r \) led to nearly the same values. In the two-pion exchange was used for the Pomeron-nucleon vertex.
It was found that the intermediate nucleon and $\Delta$ essentially cancel each other in the iso-scalar t-channel exchange, but add up in the iso-vector channel. They found $\text{Im } r \approx 0.05$.

The two gluon model for the Pomeron was used to evaluate the Pomeron spin-flip part. A quark-gluon vertex conserves helicity. This fact led to a wide spread opinion that the perturbative Pomeron has no spin-flip. This is not, however, true. The quark momenta are directed differently from the proton momentum due to transverse motion of the quarks. Therefore, the proton helicity is not equal to the sum of the quark helicities, and helicity conservation for the quarks does not mean the same for the proton.

**What distances in the proton are probed by the spin-flip Pomeron?**

It was found that the quantity $r$ is extremely sensitive to the choice of the proton wave function. For a symmetric 3-quark configuration all the contributions to the proton spin-flip amplitude cancel. Only if the proton wave function is dominated by an asymmetric quark-diquark configuration is the spin-flip amplitude nonzero. The smaller the $q\bar{q}$ separation in the diquark is, the larger is the spin-flip fraction. $\text{Im } r$ reaches nearly 10% at small $t$ if $r_D \approx 0.2 \text{ fm}$.

We conclude that the spin-flip part of the Pomeron probes the smallest distances in the proton. The smaller the minimal quark separation in the proton, the higher the virtuality of the gluons in the Pomeron has to be in order to resolve this small distance. At the same time, the non-flip part of the Pomeron probes the largest quark separation in the proton and remains nearly the same even if the diquark size tends to zero.

**The energy dependence and HERA data**

One of the main discoveries at HERA is the $Q^2$ dependence of the effective Pomeron intercept: the higher is $Q^2$, i.e. the smaller is the size of hadronic fluctuations in the virtual photon, the more the virtual photoabsorption cross section grows with energy.

As soon as the spin-flip and non-flip parts of the Pomeron probe different scales in the proton one should expect different energy dependences. To find the correlation between the effective Pomeron intercept and the size of the photon fluctuation we can use the factorized form of proton structure function:

$$F_T^p(x, Q^2) \propto \int_{c/Q^2}^{c/A^2} \frac{dr_T^2}{r_T^2} \sigma(r_T, x)$$  \hspace{1cm} (9)
The constant $c$ is of the order of one, so we fix $c = 1$.

The dipole cross section which depends on the transverse $q\bar{q}$ separation $r_T$ and the Bjorken $x$ can be parametrised as

$$\sigma(r_T, x) = \sigma(r_T) \left( \frac{1}{x} \right)^{\Delta(r_T, x)}.$$  \hfill (10)

The power $\Delta(r_T, x)$ can be interpreted as an effective Pomeron intercept, since it is nearly $x$-independent. It follows from (9) that

$$\Delta(r_T = 1/Q^2) = \frac{d}{d \ln(1/x)} \ln \left[ \frac{d}{d \ln(Q^2)} F_2^p(x, Q^2) \right].$$  \hfill (11)

We use the fit \ref{fit} to the proton structure function at $Q^2 > 1 \text{ GeV}^2$. The result for $\Delta(r_T)$ is shown in fig. 1 for few values of $x$.

![Figure 1](image)

Figure 1: The effective Pomeron intercept as function of the dipole size as found using (11) and HERA data (solid curves) at different values of $x$ shown at the curves. The dashed curves are the guessed extrapolation to the soft hadronic limit $\Delta \approx 0.08$.

It extends only up to $r_T = 0.2 \text{ fm}$ due to the restriction on $Q^2$. We know, however, that the $\Delta(r_T)$ keep monotonically decreasing at larger separations.
down to the value \( \Delta \approx 0.08 \), typical for soft hadronic interactions. The dashed curves showing the interpolation is just our guess.

The growth of \( \Delta(r_T) \) down to small \( r_T \) naturally follows from the DGLAP evolution equations in the double-leading-log approximation (e.g. Refs.\textsuperscript{14−16}). Decreasing the transverse separation \( r_T \) in the color dipole one increases the mean virtuality of the gluons which have to resolve this small structure. Therefore, one gets a larger logarithmic factor \( \ln(1/r_T) \) for each higher order correction in \( \alpha_s \). In the case of a spin-flip amplitude the mean gluon virtuality is related to the size of the diquark whose inner structure is to be resolved. In the double-leading-log approximation this causes a steeper energy dependence of the spin-flip amplitude in the same way as for the total cross section of a small-size color dipole. Therefore, we can use the \( r_T \)-dependence plotted in Fig.\textsuperscript{1} extracted from the analysis of data on \( F_2(x,Q^2) \) to estimate the value of \( \Delta \) for the spin-flip amplitude assuming that \( r_T \) is the diquark size.

We see from Fig.\textsuperscript{1} that for the diquark size which is usually believed to be \( 0.2 − 0.4 \, \text{fm} \) the effective intercept of the Pomeron spin-flip ranges within \( \Delta(r_T) \approx 0.2 − 0.3 \, \text{fm} \) \( \approx 0.2 − 0.3 \). Therefore, the fraction of the spin-flip in the Pomeron increases with energy as

\[
\text{Im } r(s) \propto \left( \frac{s}{s_0} \right)^{0.1−0.2}
\]

Such a steep growth can be easily detected with polarised proton beams at RHIC whose energy range covers (including fixed target experiments) \( 50 \, \text{GeV}^2 < s < 250000 \, \text{GeV}^2 \). The value of \( r(s) \) more than doubles in this interval. This effect can be detected in the Coulomb-nuclear interference region in the \( pp\bar{p}pp \) experiment planned at RHIC.

Summarising, we expect a rising with energy ratio of spin-flip to non-flip components of the elastic proton-proton amplitude. This prediction is based on two observations: (i) Perturbative QCD calculations show that the spin-flip amplitude is sensitive to the smallest transverse distance in the quark wave function of the proton. Since the elastic amplitude is dominated by gluonic exchanges at high energies, one can conclude that the spin-flip component probes the gluon distribution in the proton at higher virtuality than the non-flip amplitude. (ii) The proton structure function \( F_2^p(x,Q^2) \) measured at HERA rises with \( 1/x \). Data show that the higher is \( Q^2 \), the steeper is the growth of \( F_2^p(x,Q^2) \).

We conclude from (i) and (ii) that the spin-flip amplitude rises with energy faster than the non-flip one. We expect this prediction to be tested in forthcoming polarisation experiments at RHIC.
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