Probing the Pomeron spin-flip with Coulomb-nuclear interference

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Brand-new high-precision data for single-spin asymmetry \( A_N(t) \) in small angle elastic \( pp \) scattering from the fixed target experiment HJET at BNL at \( E_{lab} = 100 \) and 255 GeV, as well as high energy STAR measurements at \( \sqrt{s} = 200 \text{ GeV} \), for the first time allowed to determine the spin-flip to non-flip ratio \( r_5(t) \) in a wide energy range. We introduced essential modification in the Coulomb-nuclear interference (CNI) mechanism, missed in previous analyses. In particular, absorptive corrections make the proton electromagnetic vertex different from the formfactor, measured in electron-proton scattering. Introduction of absorptive corrections strongly affect the results for \( r_5(t) \). The Regge analysis allowed to single out the Pomeron contribution to the spin-flip amplitude, which steeply rises with energy. We found the spin-flip to non-flip ratio of the Pomeron amplitudes to be nearly \(-10\%\), rising with energy as \( s^{0.34} \), both in good accord with theoretical expectations.

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I. INTRODUCTION

The Pomeron has been introduced in the Regge theory as a rightmost singularity in the complex angular momentum plane, having vacuum quantum numbers and dominating elastic scattering amplitude at high energies. Originally it was assumed to be a Regge pole with the intercept \( \alpha_P(0) = 1 \), however later, the observed rise of the total cross sections with energy led to a higher value of the intercept \( \alpha_P(0) \) \([1]\). Besides absorptive corrections, generating Regge cuts, make the structure of the singularity.

With the advent of QCD, it was realised that the Pomeron should be modelled as gluonic exchanges in the \( t \)-channel, what naturally explains why the cross section is nearly constant, or slowly rising with energy weak rise of the cross section with energy, and why the elastic amplitude is predominantly imaginary. The spin structure of the Pomeron exchange amplitude is related to the helicity conserved quark-gluon vertex, this is why it has been widely believed that the Pomeron has no spin-flip component.

Experimental measurement of the hadronic spin-flip amplitude is a challenge. Indeed the single-spin asymmetry is proportional to \( \sin(\Delta \phi) \), where \( \Delta \phi \) is the relative phase between spin-flip and non-flip amplitudes. If the Pomeron were a Regge pole, this phase shift would be zero. Otherwise, it is expected to be small, suppressing spin effects in elastic \( pp \) scattering.

A unique opportunity to get a sizeable single-spin asymmetry \( A_N \) is to arrange interference between the almost imaginary Pomeron and real Coulomb elastic amplitudes. In this case, the relative phase is optimal for single spin asymmetry. Even if the Pomeron is spinless, the Coulomb amplitude has a known spin-flip part, due to existence of the anomalous magnetic moment of the proton, generating a considerable single-spin amplitude. This was first proposed in \([2]\), and a peculiar t-dependence of \( A_N(t) \) was found (see also \([3]\)) with a maximum of about \( 4.5\% \) at \( t = t_{\text{max}} \) with

\[
t_{\text{max}} = -\sqrt{3} \frac{8 \pi \alpha_{\text{em}}}{\sigma_{\text{tot}}} \approx -0.0025 \text{ GeV}^2.
\]

If, however, the Pomeron also has a spin-flip part, the curve \( A_N(t) \), keeping approximately the same shape, moves up or down, depending on sign and magnitude of the hadronic spin-flip. This was proposed in \([4]\) as a way to measure the Pomeron spin-flip.

In the present analysis we describe the brand-new data on \( A_N(t) \) at small \( t \) and different energies with improved formulas for the CNI mechanism. The revision, in particular, includes absorptive corrections, missed in all previous analyses, which are found to be essential, considerably affecting the results. Finally, we perform a Regge analysis in order to single out the Pomeron contribution to the hadronic spin-flip.

II. SPIN STRUCTURE OF THE ELASTIC PROTON-PROTON AMPLITUDE

The elastic \( pp \) amplitude is fully described by five independent helicity amplitudes \( \phi_i(s, t) \) \((i = 1, \ldots 5)\) defined in \([2, 3]\), each having hadronic and electromagnetic parts, \( \phi_i = \phi_i^h + \phi_i^em \).

The total and elastic cross sections and single-spin asymmetry \( A_N(t) \) are expressed via these amplitudes as,

\[
\sigma_{\text{tot}}^{pp} = 4\pi \Im(\phi_1 + \phi_3)_{t=0},
\]

\[
\frac{d\sigma_{\text{tot}}^{pp}}{dt} = 2\pi \{ |\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2 \},
\]

\[
A_N \frac{d\sigma_{\text{tot}}^{pp}}{dt} = -4\pi \Im \{ (\phi_1 + \phi_2 + \phi_3 - \phi_4)\phi_5^* \}. \tag{2}
\]

In what follows, we replace the 4-momentum transfer squared by its transverse component squared, \( t \equiv -q^2 \approx -q_T^2 \). The longitudinal momentum transfer in high-energy elastic scattering is negligibly small.
We parametrize the $s$ and $q_T$ dependences of the hadronic helicity amplitudes as,
\[
\phi_i^h (s, q_T) = \phi_i^b (s, q_T) = \frac{\alpha_{em}^{pp}(s)}{8\pi} |P_{pp}(s)| e^{-\frac{i}{2} G^{em}(s) q_T^2},
\]
where $B_{pp}(s)$ is the slope of the $pp$ elastic differential cross section, rising with energy \cite{7}. We employ here low-$q_T$ approximation and neglect the small double-flip amplitudes $\phi_2$ and $\phi_4$.

\[
r_5 \equiv \frac{8\pi M_N \phi_5^h}{q_T \sigma_{tot}^{pp}},
\]

While the magnitude of the hadronic spin-flip amplitude is questionable, the spin structure of the electromagnetic amplitude is well known,
\[
\phi_1^{em} (q_T) = \phi_3^{em} (q_T) = -\frac{\alpha_{em}}{q_T^2} G^{em}(q_T) e^{i \delta_{pp}(q_T)},
\]
\[
\phi_5^{em} (q_T) = -\frac{\alpha_{em}(\mu_p - 1)}{2M_p q_T} G^{em}(q_T) e^{i \delta_{pp}(q_T)},
\]
where we present only the amplitudes singular at $q_T \to 0$, because are interested in the low-$q_T$ region.

In \cite{6} - \cite{13} $\mu_p$ is the magnetic moment of the proton; $G(q_T)$ is the proton electromagnetic formfactor, which is taken in the small-$q_T$ form,
\[
G(q_T) = e^{-\frac{1}{2}\langle r_{em}^2 \rangle q_T^2},
\]
where $\langle r_{em}^2 \rangle$ is the proton mean charge radius squared. We fix it at the value $r_{em} = 0.875$ fm from \cite{17}.

Notice that in the parametrization proposed in \cite{3}, and used in all following analyses, the slopes of elastic $pp$ scattering and of the electromagnetic formfactor were taken equal, which is an apparent oversimplification. One of them, $B_{pp}(s)$, rises with energy, but another one is energy independent. We rely on more realistic parametrizations, explained above.

The Coulomb phase $\delta_{pp}(q_T)$ is taken in the form, calculated in \cite{5}
\[
\delta_{pp}(q_T) = \alpha_{em} e^{2\omega} [2E_1(2\omega) - E_1(\omega)],
\]
where $\omega = q_T^2 B_{pp}/4$, and $E_1(\omega)$ is the exponential integral function.

III. ABSORPTIVE CORRECTIONS

The proton electromagnetic formfactor $G(q_T)$ has been measured in electron-proton scattering, which is different from electromagnetic $pp$ scattering. While at large distances the $ep$ and $pp$ amplitudes are identical, at small impact parameters, where colliding protons overlap, they can strongly interact, and elastic scattering becomes subject to absorptive corrections.

This qualitative observation gives a hint to how these corrections can be calculated. The electromagnetic $pp$ amplitudes, Eqs. \cite{3-4} should be Fourier transformed to impact parameter representation,
\[
\phi_1^{em} (b) = -\frac{\alpha_{em}}{2\pi} \int d^2 q_T e^{i q_T \cdot \vec{b}} \frac{G^{em}(q_T)}{q_T} e^{i \delta_{pp}(q_T)},
\]
\[
\phi_5^{em} (b) = -\frac{\alpha_{em}(\mu_p - 1)}{4\pi m_p} \int d^2 q_T e^{i q_T \cdot \vec{b}} \frac{G^{em}(q_T)}{q_T} e^{i \delta_{pp}(q_T)}.
\]

Next, one should introduce the absorptive factor,
\[
\phi^{em} (b) \Rightarrow \phi^{em} (b) \times S(b),
\]
where
\[
S(b) = 1 - f_{el}^{pp}(b),
\]
and the elastic $pp$ amplitude is taken in the Gaussian form,
\[
f_{el}^{pp}(b) = \frac{\sigma_{tot}^{pp}}{4\pi B_{pp}} e^{-\frac{b^2}{2B_{pp}}}.\]

Now we are in a position to calculate the absorption corrected $q_T$-dependent helicity amplitudes by making inverse Fourier transformation to momentum representation,
\[
\tilde{\phi}_i(q_T) = \frac{1}{2\pi} \int d^2 b e^{-i q_T \cdot \vec{b}} \phi_i(b) S(b) = \phi_i(q_T) - \int db b J_0(q_T b) \phi_i(b) [1 - S(b)].
\]
The absorptive correction is given by the second term here, which is easily calculated because $1 - S(b)$ vanishes at $b^2 \gg B_{pp}$.

Notice that the hadronic amplitudes Eqs. \cite{3-4} do not need absorptive corrections, because they are parametrized in accordance with data, which include absorption by default.

IV. DATA ANALYSIS

As far as the helicity amplitudes are available, one can calculate the single-spin asymmetry $A_N(t)$ (neglecting small $\phi_2$ and $\phi_4$). We consider the low-$t$ region, where the dominant contribution comes from the interference of hadronic, Eqs. \cite{3-13}, and electromagnetic, Eqs. \cite{10-15}, amplitudes. At very high energy, we expect the former to be nearly imaginary, while the latter are almost real. Such a large phase shift allows reaching maximal interference in the single-spin asymmetry. Of course, at
medium-high energies, Reggeons can supply the amplitude with a considerable real part, but that will be taken into account in further analysis.

Since our focus is on the spin-flip component of the Pomeron, the energy should be sufficiently high to provide Pomeron dominance. STAR experiment [3] measured $A_N(t)$ at highest energy of $\sqrt{s} = 200$ GeV. Data are depicted in Fig. 1. Description of data with Eq. (2) cannot be parameter-free, as long as the hadronic spin-flip parameter $r_5$ is unknown. Its determination is the main goal of the present study. The results of the fit to the STAR data are presented in Table I. Remarkably, in contrast to the previous analysis [3] description of these data with absorptive corrections results in a nonzero $r_5$.

A much higher precision of measurements was reached in the two measurements at the fix-target experiment HJET at lab energies 255 GeV and 100 GeV [10, 11]. Data and fitted curves are depicted in Figs. 2 and 3. The corresponding values of $r_5$ are presented in Table I.

The pioneering measurements of $A_N$ in the CNI region of a small $t$ was performed back in 1993 in the E704 experiment at Fermilab [12]. Data well confirmed the prediction made in [2] with $r_5 = 0$ (see Introduction). The results are depicted in Fig. 4 and fitted in the same way as other data. The error of $\text{Im} r_5$ in this case substantially exceeds all other measurements, while $\text{Re} r_5$ has a rather small error.

![Table I: The results of the fit including absorptive corrections for the parameter $r_5$.](image)

![FIG. 1: (Color online) Data [3] at $\sqrt{s} = 200$ GeV ($E_{\text{lab}} = 21,321$ GeV) vs calculations with different values of $r_5$ ($\text{Im}, \text{Re}$). Dotted line shows the standard description [3], which prefers $r_5 = 0$. Dashed curve shows $r_5 = 0$, but with absorptive corrections added. The red solid curve presents the best fit with updated formulas.](image)

![FIG. 2: (Color online) The same as in Fig. 1 but at lab. energy 255 GeV [10, 11].](image)

![FIG. 3: (Color online) The same as in Fig. 1 but at lab. energy 100 GeV [10, 11].](image)

![FIG. 4: (Color online) The same as in Fig. 1 but at lab. energy 200 GeV [12].](image)
V. REGGE ANALYSIS

A. Spin non-flip amplitude

Pomeron
Even if the Pomeron were a true Regge pole, absorptive corrections, which are Regge cuts, essentially reduce the effective Pomeron intercept, which has been found to be \( \alpha_{\text{Pomeron}}^{nf}(0) \approx 1.08 \) [13]. We fix the intercept of the spin non-flip Pomeron at this value and parametrize the forward amplitude as,

\[
f^{nf}_P(0) = h^{nf}_P(0) \left( \frac{s}{s_0} \right)^{\alpha_{\text{Pomeron}}^{nf}(0)-1},
\]

where we fix \( s_0 = 1 \text{ GeV}^2 \). The imaginary part of the residue \( h^{nf}_P(0) \) is fitted to data on total pp cross section (together with Reggeons, see below), while the real part can be expressed with the relation derived within eikonal Regge model in [14] and within general dispersion approach in [13]. In the approximation of small \( \alpha_{\text{Pomeron}}^{nf}(0) - 1 \) this relation reads

\[
\frac{\text{Re} h^{nf}_P(0)}{\text{Im} h^{nf}_P(0)} = \frac{\pi}{2} \left( \frac{\partial \ln |\text{Im} h^{nf}_P(0)|}{\partial \ln s} \right)
\]

This relation is of course also correct for a single Pomeron, treated as an effective Regge pole.

Such a simplified effective Pomeron model fails at much higher energies, where data show the cross section rising much faster, as was predicted in [6]. However, in the restricted energy range below \( \sqrt{s} \leq 200 \text{ GeV} \), we are interested in, the model of an effective Pomeron pole well describes data [13].

Reggeons
The spin non-flip elastic pp amplitude is known from Regge phenomenology to be dominated by the Pomeron and leading Reggeons, \( f, \omega, \rho, a_2 \). Dual models predict exchange degeneracy of Reggeons with opposite signature within couples \( f - \omega \) and \( \rho - a_2 \), which cancel in the imaginary part of the pp amplitude but add up in the real part. Indeed, data on the energy dependence of the total cross section confirm such an approximate exchange degeneracy in \( p(\bar{p})p \) and \( K^+(K^-)p \) scattering. The degenerate Reggeons must have equal Regge-intercepts and residue functions. Indeed, all leading Reggeons are known to have similar intercepts \( \alpha_{\text{Reggeon}}(0) \approx 0.5 \), while the residues differ. This is why some Reggeon contribution is clearly seen in the total pp cross section, causing a fall of the cross section at medium-high energies.

We concentrate here on pp scattering and combine all Reggeons in an effective one with intercept, which we fix at \( \alpha_{\text{Reggeon}}(0) = 0.5 \) and residue factors, which we fit to data. Correspondingly, we parametrize the non-flip forward \( (t = 0) \) helicity amplitudes as,

\[
f^{nf}_R(0) = h^{nf}_R(0) \sqrt{s_0/s}
\]

Both \( \text{Re} h^{nf}_R(0) \) and \( \text{Im} h^{nf}_R(0) \) are fitted to data. The fitted values of residues in the Pomeron and Reggeon terms are collected in Table II.

| Parameter | Value                      |
|-----------|----------------------------|
| \text{Im} h^{nf}_R(0) | 2.231 \pm 0.003 \text{ GeV}^{-2} |
| \text{Re} h^{nf}_R(0) | 0.279 \pm 0.016 \text{ GeV}^{-2} |
| \text{Im} h^{nf}_R(0) | 7.767 \pm 0.110 \text{ GeV}^{-2} |
| \text{Re} h^{nf}_R(0) | -10.304 \pm 0.454 \text{ GeV}^{-2} |

TABLE II: The Regge parameters, defined in Eqs. (16) and (19), fitted to data on total pp cross section \( \sqrt{s} < 200 \text{ GeV} \) and real-to-imaginary ratio for the forward elastic amplitude.

B. Spin-flip amplitude

Pomeron
While all parameters of the spin-non-flip amplitude are well fixed by available data for total cross section and real-to-imaginary ratio for the forward elastic amplitude, those parameters for the spin-flip amplitude are essentially unknown. Our results for the hadronic spin-flip, parameter \( r_5 \), measured with CNI and presented in Table I, provide a unique opportunity to determine the magnitude and energy dependence of the spin-flip component, and separately for the Pomeron and Reggeons.

We parametrize the Pomeron spin-flip amplitude in analogy to Eqs. (16),

\[
f^{sf}_P(0) = h^{sf}_P(0) \left( \frac{s}{s_0} \right)^{\alpha_{\text{Pomeron}}^{sf}(0)-1}
\]

Here we have three parameters to be fitted to the values of \( r_5 \) in Table I, the real and imaginary part of \( h^{sf}_P(0) \) and the intercept \( \alpha_{\text{Pomeron}}^{sf}(0) \), corresponding to the Pomeron spin-flip amplitude. The latter is of special interest. If the Pomeron were a true Regge pole, this intercept would be the same as in the non-flip component, Eq. (16). However, as we have already mentioned, the Pomeron is certainly not a pole and the two intercepts, spin-flip and non-flip, are quite probably different. Moreover, the spin-flip intercept was predicted in [16] to be higher. As far as \( r_5 \) is available now in a wide range of energies, we will make an attempt to clarify this issue.

Reggeons
Reggeons are usually assumed to be Regge poles, i.e., their intercepts are universal. Indeed, while the Pomeron intercept, measured in deep-inelastic lepton scattering (DIS) at low \( x \), strongly varies with \( Q^2 \), the valence quark distribution, controlled by Reggeons, remains independent of \( Q^2 \), demonstrating universality.

Therefore we keep the same value of the intercept \( \alpha_{\text{Reggeon}}^{sf}(0) = 0.5 \) for the spin-flip amplitude. However the
residue is not universal and supplies two new fitting parameters, according to the parametrization,

\[ f_{sf}^p(0) = h_{sf}^p(0) \sqrt{s_0/s} \]  

(20)

The parameter \( r_5 \) Eq. (19) in terms of scattering amplitudes reads,

\[ r_5 = \frac{f_{sf}^p + f_{sf}^n}{\text{Im} f_{sf}^p + \text{Im} f_{sf}^n}. \]  

(21)

This function with five fitted parameters is plotted as function of energy in Fig. 5 in comparison with data points, presenting our results for \( r_5 \) from Table I

![Graph showing fitted values of \( r_5 \) as function of energy.](image)

**FIG. 5:** (Color online) Fitted values of \( r_5 \) as function of energy. The solid curve (squared points) and dashed curve (round points) correspond to imaginary and real parts of \( r_5(s) \), calculated with Eqs. (21) and (19)-(20) with fitted parameters from Table III.

| Parameter | Value                        |
|-----------|------------------------------|
| \( \text{Im} h_{sf}^p(0) \) | \(-0.0057 \pm 0.0035 \, \text{GeV}^{-2} \) |
| \( \text{Re} h_{sf}^p(0) \) | \(-0.0022 \pm 0.0012 \, \text{GeV}^{-2} \) |
| \( \text{Im} h_{sf}^n(0) \) | \(1.8300 \pm 0.3178 \, \text{GeV}^{-2} \) |
| \( \text{Re} h_{sf}^n(0) \) | \(-2.3056 \pm 0.0867 \, \text{GeV}^{-2} \) |
| \( \alpha_{Psf}(0) \) | \(1.416 \pm 0.069 \) |

TABLE III: The Regge parameters, defined in Eqs. (19) and (20) fitted to the results for \( r_5 \) presented in Table I and Fig. 4.

We arrived at the final destination of the present analysis, determination of the parameters of the spin-flip component of the Pomeron. The prominent result is the high intercept of the spin-flip Pomeron, \( \alpha_{Psf}^p - 1 \approx 0.4 \), which significantly exceeds the non-flip value \( \alpha_{Pnf}^p - 1 \approx 0.1 \). This is the first reliable measurement of the spin-flip component of the Pomeron and its energy dependence, which turns out to rise with energy much faster than the non-flip part. Such a peculiar feature of the Pomeron was predicted in [10] as a consequence of the different distances inside the proton probed by the spin-flip and non-flip parts of the Pomeron, which are sensitive to either smallest, or largest quark separations in the proton wave function, respectively [4]. The effective Pomeron intercept measured in small-\( x \) DIS at HERA was found to be considerably higher for small-size \( \bar{q}q \) dipoles (large \( Q^2 \)) in comparison with the intercept measured in soft processes, therefore a higher intercept was predicted for spin-flip Pomeron [10].

We also can determine the value of \( r_5^p(s) \) from Tables II-III.

\[ r_5^p(s) = \frac{f_{sf}^p(s)}{\text{Im} f_{sf}^p(s)}. \]  

(22)

The energy dependent \( r_5^p \) we parametrize as,

\[ r_5^p(s) = r_5^p \left( \frac{s}{s_0} \right)^\alpha_p^f(0) - \alpha_n^f(0), \]  

(23)

where according to Tables III and I,

\[ \text{Im} r_5^p = -0.00255 \pm 0.00061, \]

\[ \text{Re} r_5^p = -0.00099 \pm 0.00021, \]

\[ \alpha_p^f(0) - \alpha_n^f(0) = 0.336 \pm 0.069. \]  

(24)

Notice that although these values look quite small, the second, energy dependent factor in (23) grossly enhances \( r_5^p \). E.g., at \( \sqrt{s} = 200 \, \text{GeV} \) \( \text{Im} r_5^p = -0.09 \), which is in a good accord with the predicted in [4] value of about \(-10\% \) (see also [3]). Since at this energy the Pomeron dominance is expected, one can also compare it with the full \( r_5 \) plotted in Fig. 6.

Eq. (23) is the main result of the present analysis, the first reliable determination of the Pomeron spin-flip component, and its energy dependence.

An alternative analysis of the same data was performed recently [11]. Besides some minor differences in the Regge analysis and the CNI formula for \( A_N \), the main discrepancy is due to absorptive corrections, missed in [11], which are crucial for the analysis. As we demonstrated, they drastically affect the results and conclusions. In particular, the sign of \( r_5 \) in [11] is opposite to ours.

VI. PREDICTIONS

Following the planning measurements if \( A_N(t) \) by the STAR collaboration at maximal RHIC energy of \( \sqrt{s} = 510 \, \text{GeV} \), we extrapolated our results to this energy, relying upon the Regge parametrization presented in Tables II-III and Eq. (23). Our prediction for \( A_N(t) \) is depicted in Fig. 6.

VII. SUMMARY

The main new results of the present analysis can be formulated as follows.
Electromagnetic proton formfactor in elastic Coulomb $pp$ scattering is different from one, measured in $ep$ scattering, due to strong absorption effects at small impact parameters. We calculated the absorptive corrections to the CNI mechanism of single-spin asymmetry $A_N$ and found a significant difference with previous analyses.

Novel analysis of high-precision data for $A_N(t)$ from fixed target experiments HJET at $E_{lab} = 100$ and 255 GeV, and high energy STAR measurements at $\sqrt{s} = 200$ GeV determine new set of the results for spin-flip to non-flip ratio $r_5(t)$.

High precision of data and wide energy range allows to perform Regge analysis of the observed energy dependence of $r_5$ and to single out the Pomeron contribution. This is the first successful and reliable determination of the Pomeron spin-flip component, the main goal of the present study.

Since the Pomeron is well known not to be a Regge pole, the effective intercept of its spin-flip component does not coincide with the intercept measured in spin averaged soft processes. Our analysis revealed a considerably higher intercept of the Pomeron spin-flip, in good accord with theoretical expectations. This is the most astonishing result of the present study.

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