POSSIBLE ODDERON EFFECTS
IN HADRON-NUCLEON SCATTERING

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Abstract

We consider the possible contribution of Odderon (Reggeon with $\alpha_{Odd}(0) \sim 1$ and negative signature) exchange to the differences in the total cross sections of particle and antiparticle, to the ratios of real/imaginary parts of the elastic $pp$ amplitude, and to the differences in the inclusive spectra of particle and antiparticle in the central region. The experimental differences in total cross sections of particle and antiparticle are compatible with the existence of the Odderon component but such a large Odderon contribution seems to be inconsistent with the values of Re/Im ratios. In the case of inclusive particle and antiparticle production the current energies and/or accuracy of the experimental data don’t allow a clear conclusion.

PACS. 25.75.Dw Particle and resonance production
1 Introduction

The Odderon is a singularity in the complex $J$-plane with intercept $\alpha_{Od} \sim 1$, negative $C$-parity, and negative signature. Thus its zero flavour-number exchange contribution to particle-particle and to antiparticle-particle interactions, e.g., to $pp$ and $\bar{p}p$ total cross sections, has opposite signs. In QCD the Odderon singularity is connected [1] to the colour-singlet exchange of three reggeized gluons in $t$-channel. The theoretical and experimental status of Odderon has been recently discussed in refs. [2, 3]. The possibility to detect Odderon effects has also been investigated in other domains as charm photoproduction [4].

The difference in the total cross sections of antiparticles and particles interactions with nucleon targets are numerically small and decrease rather fast with initial energy, so the Odderon coupling should be very small with respect to the Pomeron coupling. However, several experimental facts favouring the presence of the Odderon contribution exist. One of them is the difference in the $d\sigma/dt$ behaviour of elastic $pp$ and $\bar{p}p$ scattering at $\sqrt{s} = 52.8$ GeV and $|t| = 1. - 1.5$ GeV$^2$ presented in references [2, 5]. Also the differences in the yields baryons and antibaryons produced in the central (midrapidity) region and in the forward hemisphere in meson-nucleon and in meson-nucleus collisions, and in the midrapidity region of high energy $pp$ interactions [6, 7, 8, 9, 10, 11], can also be significant in this respect. The question of whether the Odderon exchange is needed for explaining these experimental facts, or they can be described by the usual exchange of a reggeized quark-antiquark pair with $\alpha_\omega(t) = \alpha_\omega(0) + \alpha'_\omega t$ ($\omega$-Reggeon exchange) is a fundamental one.

The detailed description of all available data on hadron-nucleon elastic scattering with accounting for Regge cuts results in $\alpha_\omega(0) = 0.43$, $\alpha'_\omega = 1$ GeV$^{-2}$ [12], and the simplest power fit

$$\Delta \sigma_{hp} = \sigma^\text{tot}_{hp} - \sigma^\text{tot}_{hp} = \sigma_R \cdot (s/s_0)^{\alpha_R(0)-1}$$

for experimental points of $\bar{p}p$ and $pp$ scattering starting from $\sqrt{s} = 5$ GeV gives the value $\alpha_R = 0.424 \pm 0.015$ [13]. The accounting for Regge cut contributions of the type $RP$, $RPP$, $RP...P$, and $Rf$, $RfP$, $RfP...P$ slightly decrease [13] the effective value of $\alpha_R$. Thus any process with exchange of a negative signature object with effective intercept $\alpha_{eff} > 0.7$ could be considered as an Odderon contribution, while if $\alpha_{eff} \leq 0.5$ one could say that there is no room for the Odderon contribution.

In this paper we carry out this analysis for the case of high energy $hp$ collisions. In Section 2 we study the Regge pole contributions from the data on $\bar{p}p$, $pp$, $\pi^\pm p$, and $K^\pm p$ total cross sections. In Section 3 we consider the possible Odderon effect on the ratios of real/imaginary parts of the elastic $pp$ amplitude. In Section 4 we take into
account the ratios of $\bar{p}$ to $p$ inclusive production in the midrapidity (central) region of $pp$ collisions, and, finally, in Sections 5 and 6 we compare these experimental data with the theoretical predictions of the Quark–Gluon String Model (QGSM).

2 Regge-pole analysis of total $hp$ and $\bar{h}p$ cross sections

Let us start from the analysis of high energy elastic particle and antiparticle scattering on the proton target. Here the simplest contribution is the one Regge-pole $R$ exchange corresponding to the scattering amplitude

$$A(s, t) = g_1(t) \cdot g_2(t) \cdot \left( \frac{s}{s_0} \right)^{\alpha_R(t)-1} \cdot \eta(\theta),$$

(2)

where $g_1(t)$ and $g_2(t)$ are the couplings of a Reggeon to the beam and target hadrons, $\alpha_R(t)$ is the $R$-Reggeon trajectory, and $\eta(\theta)$ is the signature factor which determines the complex structure of the scattering amplitude ($\theta$ equal to +1 and to -1 for reggeon with positive and negative signature, respectively):

$$\eta(\theta) = \begin{cases} i - \tan^{-1}(\frac{\pi \alpha_R}{2}) & \theta = +1 \\ i + \tan(\frac{\pi \alpha_R}{2}) & \theta = -1 \end{cases},$$

(3)

so the amplitude $A(s, t = 0)$ becomes purely imaginary for positive signature and purely real for negative signature when $\alpha_R \rightarrow 1$.

The contribution of the Reggeon exchange with positive signature is the same for a particles and its antiparticle, but in the case of negative signature the two contributions have opposite signs, as it is shown in Fig. 1.

The difference in the total cross section of high energy particle and antiparticle scattering on the proton target is

$$\Delta \sigma_{hp}^{tot} = \sum_{R(\theta = -1)} 2 \cdot Im A(s, t = 0) = \sum_{R(\theta = -1)} 2 \cdot g_1(0) \cdot g_2(0) \cdot \left( \frac{s}{s_0} \right)^{\alpha_R(0)-1} \cdot Im \eta(\theta = -1).$$

(4)

The experimental data for the differences of $\bar{p}p$ and $pp$ total cross sections are presented in Fig. 2. Here we use the data compiled in ref. [14] by presenting at every energy the experimental points for $pp$ and $\bar{p}p$ by the same experimental group and with the smallest error bars. At ISR energies (last three points in Fig. 2) we present the data in ref. [15] as published in their most recent version.
In the left panel of Fig. 2 our fit to the experimental data with Eq. (1) starting from $\sqrt{s} > 8$ GeV is presented (solid line). For this fit we obtain the value of $\alpha_R = 0.43 \pm 0.017$ with $\chi^2 = 33.3/15$ ndf. This result is in good agreement with [13], where the experimental points at energies $\sqrt{s} > 5$ GeV were included in the fit, and it only slightly differs from the general fit of all $hp$ total cross sections [16] which results in

$$\Delta \sigma_{pp} = 42.31 \cdot s^{-0.4525} \text{mb},$$

and it starts from $\sqrt{s} > 10$ GeV. This last fit is also shown in Fig. 2 by a dashed line. The values of the parameters for the two fits, together with the $\chi^2$ values, are presented in Table 1. It is needed to note that the fit in [16] was aimed at the total $\bar{p}p$ and $pp$ cross sections, not specifically at their differences, and so the not very good values of $\chi^2$ for this fit are not very significant.

| Parameterization | $\sigma_R (mb)$ | $\alpha_R (0)$ | $\chi^2/ndf$ |
|------------------|-----------------|----------------|---------------|
| $p^\pm p, \sqrt{s} > 8$ GeV (Eq. (1)) | 75.4 $\pm$ 6.1 | 0.43 $\pm$ 0.017 | 35.1/15 |
| $p^\pm p, \sqrt{s} > 13$ GeV (Eq. (1)) | 25.5 $\pm$ 7.1 | 0.625 $\pm$ 0.05 | 8.8/10 |
| $p^\pm p, \sqrt{s} > 8$ GeV (Eq. (5)) | 42.31 (fixed) | 0.5475 (fixed) | 92.3/17 |
| $p^\pm p, \sqrt{s} > 13$ GeV (Eq. (5)) | 42.31 (fixed) | 0.5475 (fixed) | 34.5/12 |
| $\pi^\pm p, \sqrt{s} > 8$ GeV (Eq. (1)) | 9.51 $\pm$ 1.89 | 0.51 $\pm$ 0.04 | 17.2/20 |
| $\pi^\pm p, \sqrt{s} > 8$ GeV (Eq. (5)) | 8.46 (fixed) | 0.5475 (fixed) | 26.3/22 |
| $K^\pm p, \sqrt{s} > 8$ GeV (Eq. (1)) | 28.0 $\pm$ 3.7 | 0.45 $\pm$ 0.03 | 15.4/18 |
| $K^\pm p, \sqrt{s} > 8$ GeV (Eq. (5)) | 8.46 (fixed) | 0.5475 (fixed) | 50.1/20 |

Table 1: The Regge-pole fits of the differences in $\bar{h}p$ and $hp$ total cross sections by using Eq. (1) and Eq. (5).
Figure 2: Experimental differences of $\bar{p}p$ and $pp$ total cross sections at $\sqrt{s} > 8$ GeV (left panel) and at $\sqrt{s} > 13$ GeV (right panel) together with their fit by Eq. (1) (solid curves), fit of Eq. (5) (dashed curves) and fit by Eq. (6) (dash-dotted curves).

As one can see in Table 1, the Eq. (1) fit can only describe the experimental difference in the total $\bar{p}p$ and $pp$ cross sections when starting from highly enough energies. When starting at lower energies other Regge poles, as well as other contributions, can contribute, but their contribution becomes negligible at higher energies. Thus the values of the parameters in Eq. (1) can be different in different energy regions. To check the stability of the parameter values, we present in the right panel of Fig. 2 the same experimental data as in the left panel, but at $\sqrt{s} > 13$ GeV. Here we obtain $\alpha_R = 0.62 \pm 0.05$ with $\chi^2 = 8.3/10$ n.d.f., i.e. now the description of the data is better, with the value of $\alpha_R$ significantly increasing. This indicates that it is reasonable to account for two contributions to $\Delta \sigma_{pp}$, the first one corresponding to the well-known $\omega$-reggeon and the second one corresponding to a possible Odderon exchange:

$$\Delta \sigma_{hp} = \sigma_\omega \cdot (s/s_0)^{\alpha_\omega(0)-1} + \sigma_{Odd} \cdot (s/s_0)^{\alpha_{Odd}(0)-1}.$$  \hspace{1cm} (6)

The accuracy of the available experimental points is not good enough for the determination of the values of the four parameters in Eq. (6), so by sticking to the idea of existence of the Odderon, we have fixed the value of $\alpha_{Odd}(0)$ close to one (we take $\alpha_{Odd}(0) = 0.9$), and we obtain the fit shown by a dash-dotted curve both in the left panel and in the right panel of Fig. 2 with the values of the parameters presented in Table 2.
Table 2: The double Regge-pole fit to the differences in $\bar{h}p$ and $hp$ total cross sections using Eq. (6).

From the results of this fit for $\sqrt{s} > 8\text{ GeV}$ one can see that an Odderon contribution with $\alpha_{\text{Odd}}(0) \sim 0.9$ is in agreement with the experimental data, the values of $\chi^2/\text{ndf}$ for parametrization by Eq. (6) being smaller than those in the case of Eq. (1). The contributions of Odderon and $\omega$-reggeon to the differences in $\bar{p}p$ and $pp$ total cross sections would be approximately equal at $\sqrt{s} \sim 25-30\text{ GeV}$. The fit with Eq. (6) at $\sqrt{s} > 13\text{ GeV}$ qualitatively results in the same curve as the fit at $\sqrt{s} > 8$, but now the errors in the values of the parameters are very large.

Such large value of $\alpha_{\text{Odd}}(0)$ ($\alpha_{\text{Odd}}(0) \sim 0.9$) with a rather large Odderon coupling should necessarily reflect in a large value of the ratio

$$\rho = \frac{\text{Re}A(s, t = 0)}{\text{Im}A(s, t = 0)},$$

but this could be in disagreement with the existing experimental data, as it will be discussed in the next section. In any case, this problem becomes fades away when considering smaller values of $\alpha_{\text{Odd}}(0)$. For this reason in Table 2 we present our fits for the differences in $\bar{h}p$ and $hp$ total cross sections by using Eq. (6) with a fixed value $\alpha_{\text{Odd}}(0) = 0.8$. The new curves are very close to those of the $\alpha_{\text{Odd}}(0) = 0.9$ fit, but now the values of $\chi^2/\text{ndf}$ are slightly increased.

In the left panel of Fig. 3 the experimental data for the differences of $\pi^- p$ and $\pi^+ p$ total cross sections taken from [13] are shown, together with the power fit of Eq. (1) (solid line), the fit in ref. [16] (dashed curve), and the double Reggeon fit of Eq. (6) with a value $\alpha_{\text{Odd}}(0) = 0.9$ (dash-dotted curve).

Since the Odderon corresponds to a three-gluon exchange, it can not contribute to the difference in $\pi^- p$ and $\pi^+ p$ total cross sections, what is consistent with our results, the values of $\chi^2/\text{ndf}$ being practically the same for the solid and dash-dotted curves in Fig. 3, while the value of $\sigma_{\text{Odd}}$ is compatible with zero.

Similar results for the differences in $K^- p$ and $K^+ p$ total cross sections are shown in right panel of Fig. 3. Now a small Odderon contribution can exist due to the different
Figure 3: The experimental differences in $\pi^- p$ and $\pi^+ p$, left panel (and in $K^- p$ and $K^+ p$, right panel) total cross sections, together with their fits by Eq. (1) (solid curves), by ref. [16] (dashed curves), and by Eq. (6) (dash-dotted curves).

couplings of light and strange quarks to the reggeized gluons. However, our double Reggeon fit is again compatible with a zero Odderon contribution.

Needless to say, the presented results do not prove the Odderon existence in $pp$ scattering. We can only say that the assumption of the presence of an Odderon contribution is consistent with the experimental data on total $pp$ and $\bar{p}p$ cross sections. In any case, a more detailed analysis is needed, especially concerning the experimental error bars for the differences in $pp$ and $\bar{p}p$ cross sections. Thus, we have considered independent experimental values of the $pp$ and $\bar{p}p$ cross sections, but the experimental error bars in their differences would decreased if both were measured with the same experimental equipment.

3 Odderon contribution to the ratio Re/Im parts of elastic $pp$ amplitude

As one can see from Eqs. (2) and (3) the Odderon exchange generates a large real part of the elastic $pp$ amplitude which is proportional to $\tan(\frac{\pi\alpha_R}{2})$. The singularity at $\alpha_R = 1$ should be compensated by the smallness of the corresponding coupling. In the
normalization, where \( ImA_{hp} = \sigma_{hp}^{tot} \), one has

\[
ReA_{Odd} = \frac{1}{2} (\sigma_{pp}^{tot} - \sigma_{pp}^{tot})_{Odd} \cdot \tan \left( \frac{\pi \alpha_{R}}{2} \right),
\]

and the additional contribution by the Odderon to the total \( \rho = ReA_{pp}/ImA_{pp} \) value it would be equal to

\[
\rho_{Odd} = \frac{ReA_{Odd}}{\sigma_{pp}^{tot}}.
\]

Table 2 and Fig. 2 show that the possible Odderon contribution to the difference in the total \( pp \) and \( \bar{p}p \) cross sections is of the order of the positive signature (mainly Pomeron) contribution at \( \sqrt{s} \approx 25-30 \text{ GeV} \) and of about one half of the positive signature contribution at \( \sqrt{s} \approx 10 \text{ GeV} \). So, in the case of \( \alpha_{Odd}(0) = 0.9 \) the value of \( ReA_{Odd} \) in Eq. (8) can be \( ReA_{Odd} \approx 3-4 \text{ mb} \), what would result in an additional \( \rho_{Odd} = 0.07-0.1 \) contribution to the total \( ReA_{pp}/ImA_{pp} \) ratio. This additional Odderon contribution would disagreement with the experimental data presented in Table 3.

| Experiment | \( \sqrt{s} \) (GeV) | \( \rho(s) \) | Theory |
|------------|---------------------|--------------|--------|
| \( \sqrt{s} = 13.7 \text{ GeV} \) [17] | \(-0.092 \pm 0.014\) | \(-0.085 \pm 0.18\) |
| \( \sqrt{s} = 13.7 \text{ GeV} \) [19] | \(-0.074 \pm 0.018\) | \(-0.085 \pm 0.18\) |
| \( \sqrt{s} = 15.3 \text{ GeV} \) [19] | \(-0.024 \pm 0.014\) | \(-0.060 \pm 0.18\) |
| \( \sqrt{s} = 16.8 \text{ GeV} \) [17] | \(-0.040 \pm 0.014\) | \(-0.047 \pm 0.18\) |
| \( \sqrt{s} = 16.8 \text{ GeV} \) [19] | \(0.008 \pm 0.017\) | \(-0.047 \pm 0.18\) |
| \( \sqrt{s} = 18.1 \text{ GeV} \) [19] | \(-0.011 \pm 0.019\) | \(-0.04 \pm 18\) |
| \( \sqrt{s} = 19.4 \text{ GeV} \) [19] | \(0.019 \pm 0.016\) | \(-0.033 \pm 18\) |
| \( \sqrt{s} = 21.7 \text{ GeV} \) [17] | \(-0.041 \pm 0.014\) | \(-0.02 \pm 18\) |
| \( \sqrt{s} = 23.7 \text{ GeV} \) [17] | \(-0.028 \pm 0.016\) | \(-0.007 \pm 18\) |
| \( \sqrt{s} = 30.6 \text{ GeV} \) [20] | \(0.042 \pm 0.011\) | \(0.03 \pm 18\) |
| \( \sqrt{s} = 44.7 \text{ GeV} \) [20] | \(0.062 \pm 0.011\) | \(0.062 \pm 18\) |
| \( \sqrt{s} = 52.9 \text{ GeV} \) [20] | \(0.078 \pm 0.010\) | \(0.075 \pm 18\) |
| \( \sqrt{s} = 62.4 \text{ GeV} \) [20] | \(0.095 \pm 0.011\) | \(0.084 \pm 18\) |
| \( \sqrt{s} = 546 \text{ GeV} \) [21] | \(0.24 \pm 0.04\) | \(0.10-0.15 \pm 21\) |
| \( \sqrt{s} = 541 \text{ GeV} \) [22] | \(0.135 \pm 0.015\) | \(0.12-0.15 \pm 23, 24\) |

Table 3: Experimental data for the ratio Re/Im parts of elastic \( pp \) amplitude at high energies together with the corresponding theoretical estimations.

In fact, the experimental data in refs. [17, 20] are in good agreement with the theoretical estimations based on the dispersion relations without Odderon contribution
so the hypothetical Odderon contribution could be as much of the order of the experimental error bars. The same situation appears at the CERN-SPS energy \[22\]. On the other hand, the experimental points \[19, 21\] allows some room for the presence of the Odderon contribution. It is necessary keep in mind that the theoretical predictions also has some ”error bars”, for example the predictions for UA4 energy presented in \[22\] are between $\rho = 0.12 \ [23]$ and $\rho = 0.15 \ [24]$.

Let us note that the level of disagreement of the theoretical estimations on $\rho_{Odd}$ with experimental data decreases when decreasing the value of $\alpha_{Odd}$.

## 4 Regge-pole analysis of inclusive particle and antiparticle production in the central region

The inclusive cross section of the production of a secondary $h$ in high energy $pp$ collisions in the central region is determined by the Regge-pole diagrams shown in Fig. 4 \[25\]. The diagram with only Pomeron exchange (Fig. 4a) is the leading one, while the diagrams with one secondary Reggeon $R$ (Figs. 4b and 4c) correspond to corrections which disappear with the increase of the initial energy.

$$F(p_T, s_1, s_2, s) = \frac{1}{\pi^2 s} g_{R}^{pp} \cdot g_{P}^{pp} \cdot g_{Rb}(p_T) \cdot \left(\frac{s_1}{s_0}\right)^{\alpha_R(0)} \cdot \left(\frac{s_2}{s_0}\right)^{\alpha_P(0)},$$

(10)

where

$$s_1 = (p_a + p_h)^2 = m_T \cdot s^{1/2} \cdot e^{-y^*},$$

$$s_2 = (p_b + p_h)^2 = m_T \cdot s^{1/2} \cdot e^{y^*},$$

(11)
with \( s_1 \cdot s_2 = m_T^2 \cdot s \), and the rapidity \( y^* \) defined in the center-of-mass frame.

The contribution of diagram in Fig. 4c differs from Eq. (10) in the change of \( s_1 \) by \( s_2 \) and vice versa, and in the contribution of the diagram in Fig. 4a is obtained from Eq. (10) by changing the Reggeon \( R \) by Pomeron \( P \).

Let us consider the \( R \)-Reggeon in Fig. 4 as the effective sum of all amplitudes with negative signature, so its contribution to the inclusive spectra of secondary protons and antiprotons has the opposite sign. In the midrapidity region, i.e. at \( y^* = 0 \), the ratios \((\langle m_T \rangle \approx 1 \text{ GeV})\) of \( p \) and \( \bar{p} \) yields integrated over \( p_T \) can be written as

\[
\frac{\bar{p}}{p} = \frac{1 - r_-(s)}{1 + r_-(s)},
\]

where \( r_-(s) \) is the ratio of the negative signature (\( R \)) to the positive signature (\( P \)) contributions:

\[
r_-(s) = c_1 \cdot \left( \frac{s}{s_0} \right)^{(\alpha_R(0) - \alpha_P(0))/2},
\]

and \( c_1 \) is a normalization constant.

The theoretical fit by Eq. (12) to the experimental data [27, 28, 29, 30, 31, 32] on the ratios of \( \bar{p}/p \) production cross sections at \( y^* = 0 \) is presented in Fig. 5. Here we have used four experimental points from RHIC, obtained by BRAHMS, PHOBOS, PHENIX, and STAR Collaborations, and we present both \( \bar{p}/p \) and \( 1 - \bar{p}/p \) as functions of initial energy. The obtained values of the parameters \( c_1 \) and \( \alpha_R(0) - \alpha_P(0) \) are presented in Table 4.

| Parameterization | \( c_1 \) | \( \alpha_R(0) - \alpha_P(0) \) | \( \chi^2/\text{ndf} \) |
|------------------|----------|-----------------|-----------------|
| \( \bar{p}/p \) (Eq. (13), Fig. 5) | \( 4.4 \pm 1.1 \) | \( -0.71 \pm 0.07 \) | \( 4.3/8 \) |
| \( K^-/K^+ \) (Eq. (13), Fig. 6) | \( 2.8 \pm 2.6 \) | \( -0.90 \pm 0.27 \) | \( 2.0/8 \) |
| \( \bar{p}/p \) (Eq. (14), Fig. 7) | \( 4.0 \pm 0.7 \) | \( -0.79 \pm 0.04 \) | \( 15.0/8 \) |
| \( K^-/K^+ \) (Eq. (14), Fig. 7) | \( 2.3 \pm 0.8 \) | \( -0.99 \pm 0.12 \) | \( 10.0/7 \) |
| \( \pi^-/\pi^+ \) (Eq. (14), Fig. 7) | \( 0.44 \pm 0.12 \) | \( -0.98 \pm 0.11 \) | \( 34.5/7 \) |

Table 4: The Regge-pole fit of the experimental ratios of \( \bar{hp} \) and \( hp \) total cross sections by using Eqs. (12) and (13), and by using Eqs. (12) and (15).

The value of difference of \( \alpha_R(0) - \alpha_P(0) \) obtained in the fit seems to be too large for allowing the presence of an Odderon contribution.

The corresponding fit of the experimental data [27, 28, 29, 30, 31, 32] on the ratios of \( K^- \) to \( K^+ \) production cross sections at \( y^* = 0 \) is presented in Fig. 6, again for \( K^-/K^+ \) and \( 1 - K^-/K^+ \) as functions of the initial energy. The values of the parameters obtained
in the fit are also presented in Table 3. The value of \( \alpha_R(0) - \alpha_P(0) \) obtained in the \( K^-/K^+ \) is compatible with the value obtained in the \( \bar{p}/p \) fit.

It is needed to note that both fits in Figs. (5) and (6) are in fact normalized to the experimental point in ref. [28], since the error bar of this point is several times smaller than those of the other considered experimental data.

The ratios of \( \pi^- \) over \( \pi^+ \) production cross sections in midrapidity region \( y^* = 0 \) differ from unity only at moderate energies where different processes can contribute. At higher energies, where the applicability of Regge-pole asymptotics seems to be reasonable, these ratios are very close to one, so they can not be used in our analysis.

Though the experimental points for antiparticle/particle yield ratios obtained by different Collaborations at RHIC energy \( \sqrt{s} = 200 \text{ GeV} \) are in reasonable agreement with each other (see Figs. 5 and 6), the BRAHMS Collaboration results are of special interest because they were obtained not only at \( y^* = 0 \), but also at different values of non-zero rapidity \( y^* \), and they can then provide some additional information.

Thus we present in the right panels of Figs. 5 and 6 the results of the fit to the same experimental data [27, 28] at \( \sqrt{s} < 70 \text{ GeV} \), but only considering BRAHMS Collaboration experimental point at RHIC energy (dashed curves). In the case of the \( \bar{p} \) to \( p \) ratio the result of this fit is practically the same as with all four RHIC points (solid curve in Fig. 5). However in the case of the \( K^- \) to \( K^+ \) ratio the fit with only the
Figure 6: Ratios of $K^-$ to $K^+$ production cross sections in high energy $pp$ collisions at $y^* = 0$, together with their fit by Eq. (12) (solid curves). Dashed curve shows the result of the fit with only BRAHMS point at RHIC energy.

BRAHMS Collaboration experimental point (dashed curve) significantly differs from the solid curve, meaning that the energy dependence of the $K^-$ to $K^+$ experimental ratio is very poorly known.

For the case of inclusive production at some rapidity distance $y^* \neq 0$ from the c.m.s. the quantity $r_-(s, y^*)$ in Eq. (12) takes the form:

$$r_-(s, y^*) = \frac{c_1}{2} \left( \frac{s}{s_0} \right)^{(\alpha_R(0) - \alpha_P(0))/2} \cdot \left( e^{y^*(\alpha_R(0) - \alpha_P(0))} + e^{-y^*(\alpha_R(0) - \alpha_P(0))} \right). \quad (14)$$

In Fig. 7 we present the fit to the experimental rapidity distribution ratios $\bar{p}/p$ (left panel), $K^-/K^+$ (right panel), and $\pi^-/\pi^+$ (lower panel) at $\sqrt{s} = 200$ GeV [29] by using Eq. (14). The values of parameters obtained in this fit are in agreement with those in the fits of Figs. 5 and 6 (see Table 3), so we can arguably claim that in the framework of Regge-pole phenomenology one gets a model independent description of the rapidity dependence of the $\bar{p}/p$ and $K^-/K^+$ ratios by using the values of the parameters that were obtained in the description of the energy dependence of these ratios at $y^* = 0$ using Eq. (12).

The values of $\alpha_R(0) - \alpha_P(0)$ for the $K^-/K^+$ and $\pi^-/\pi^+$ ratios are the same and they seem to be larger than the value for the $\bar{p}/p$ ratio. This situation is qualitatively similar to that of the differences in the total cross sections considered in Section 2.

However, the fit $\bar{p}/p$ ratios provide values of $\alpha_R(0) - \alpha_P(0)$ significantly larger than those one could expect if the Odderon contribution was present.
Figure 7: Ratios of the inclusive cross sections $\bar{p}$ to $p$ (left panel), $K^-$ to $K^+$ (right panel), and $\pi^-$ to $\pi^+$ (lower panel) in $pp$ collisions at $\sqrt{s} = 200$ GeV \cite{29} as function of the c.m. rapidity, together with their fit by Eq. (14) (solid curves).

5 Inclusive spectra of secondary hadrons in the Quark-Gluon String Model

The ratios of inclusive production of different secondaries can also be analyzed in the framework of the Quark-Gluon String Model (QGSM) \cite{33, 34, 35}, which allows us to make quantitative predictions at different rapidities including the target and beam fragmentation regions. In QGSM high energy hadron-nucleon collisions are considered as taking place via the exchange of one or several Pomerons, all elastic and inelastic processes resulting from cutting through or between Pomerons \cite{36}.

Each Pomeron corresponds to a cylindrical diagram (see Fig. 8a), and thus, when
cutting one Pomeron, two showers of secondaries are produced as it is shown in Fig. 8b. The inclusive spectrum of a secondary hadron $h$ is then determined by the convolution of the diquark, valence quark, and sea quark distributions $u(x, n)$ in the incident particles with the fragmentation functions $G^h(z)$ of quarks and diquarks into the secondary hadron $h$. These distributions, as well as the fragmentation functions are constructed using the Reggeon counting rules [37]. Both the diquark and the quark distribution functions depend on the number $n$ of cut Pomerons in the considered diagram.

![Diagram](image)

Figure 8: Cylindrical diagram corresponding to the one–Pomeron exchange contribution to elastic $pp$ scattering (a), and the cut of this diagram which determines the contribution to the inelastic $pp$ cross section (b). Quarks are shown by solid curves and string junction by dashed curves.

For a nucleon target, the inclusive rapidity or Feynman-$x$ ($x_F$) spectrum of a secondary hadron $h$ has the form [33]:

$$\frac{d n}{d y} = \frac{x_E}{\sigma_{inel}} \cdot \frac{d \sigma}{d x_F} = \sum_{n=1}^{\infty} w_n \cdot \phi_n^h(x), \tag{15}$$

where the functions $\phi_n^h(x)$ determine the contribution of diagrams with $n$ cut Pomerons and $w_n$ is the relative weight of this diagram. Here we neglect the contribution of diffraction dissociation processes which is very small in the midrapidity region.

For $pp$ collisions

$$\phi_{pp}^h(x) = f_{qq}^h(x_+, n) \cdot f_q^h(x_-, n) + f_q^h(x_+, n) \cdot f_{qq}^h(x_-, n) + 2(n-1)f_s^h(x_+, n) \cdot f_s^h(x_-, n), \tag{16}$$

$$x_\pm = \frac{1}{2} \left[ \sqrt{4m_T^2/s + x^2} \pm x \right], \tag{17}$$

where $f_{qq}$, $f_q$, and $f_s$ correspond to the contributions of diquarks, valence quarks, and sea quarks, respectively.
These functions are determined by the convolution of the diquark and quark distributions with the fragmentation functions, e.g. for the quark one can write:

$$f_h^q(x_+, n) = \int_{x_+}^{1} u_q(x_1, n) \cdot G_h^q(x_+/x_1) dx_1 .$$

(18)

The diquark and quark distributions, which are normalized to unity, as well as the fragmentation functions, are determined by the corresponding Regge intercepts [37].

At very high energies both $x_+$ and $x_-$ are negligibly small in the midrapidity region and all fragmentation functions, which are usually written [37] as $G_h^q(z) = a_h(1 - z)^\beta$, become constants that are equal for a particle and its antiparticle (this would correspond to the limit $r_-(s) \to 0$ in Eq. (12)):

$$G_h^q(x_+/x_1) = a_h .$$

(19)

This leads, in agreement with [25], to

$$\frac{dn}{dy} = g_h \cdot (s/s_0)^{\alpha_p(0) - 1} \sim a_h^2 \cdot (s/s_0)^{\alpha_p(0) - 1} ,$$

(20)

that corresponds to the only one-Pomeron exchange diagram in Fig. 4a, the only diagram contributing to the inclusive density in the central region (AGK theorem [36]) at asymptotically high energy. The intercept of the supercritical Pomeron $\alpha_p(0) = 1 + \Delta$, $\Delta = 0.139$ [35], is used in the QGSM numerical calculations.

In the string models, baryons are considered as configurations consisting of three connected strings (related to three valence quarks) called string junction (SJ) [38, 39, 40, 41]. The colour part of a baryon wave function reads as follows [38, 40] (see Fig. 9):

$$B = \psi_i(x_1) \cdot \psi_j(x_2) \cdot \psi_k(x_3) \cdot J^{ijk}(x_1, x_2, x_3, x) ,$$

(21)

$$J^{ijk}(x_1, x_2, x_3, x) = \Phi_i^\prime(x_1, x) \cdot \Phi_j^\prime(x_2, x) \cdot \Phi_k^\prime(x_3, x) \cdot \epsilon^{ijk} ,$$

(22)

$$\Phi_i^\prime(x_1, x) = \left[ T \cdot \exp \left( g \cdot \int_{P(x_1, x)} A_\mu(z) dz^\mu \right) \right]_{i}^{\prime} ,$$

(23)

where $x_1, x_2, x_3,$ and $x$ are the coordinates of valence quarks and SJ, respectively, and $P(x_1, x)$ represents a path from $x_1$ to $x$ which looks like an open string with ends at $x_1$ and $x$. Such a baryon structure is supported by lattice calculations [42].
This picture leads to some general phenomenological predictions. In particular, it opens room for exotic states, such as the multiquark bound states, 4-quark mesons, and pentaquarks [40, 43, 44]. In the case of inclusive reactions the baryon number transfer to large rapidity distances in hadron-nucleon and hadron-nucleus reactions can be explained [6, 7, 8, 9, 10, 11] by SJ diffusion.

The production of a baryon-antibaryon pair in the central region usually occurs via $SJ$-$\bar{SJ}$ (according to Eq. (23) SJ has upper color indices, whereas antiSJ ($\bar{SJ}$) has lower indices) pair production which then combines with sea quarks and sea antiquarks into, respectively, $BB\bar{B}$ pair [40, 45]. In the case of $pp$ collisions the existence of two SJ in the initial state and their diffusion in rapidity space lead to significant differences in the yields of baryons and antibaryons in the midrapidity region even at rather high energies [6, 8].

The quantitative theoretical description of the baryon number transfer via SJ mechanism was suggested in the 90’s when the at that time latest experimentally observed [46] $p/\bar{p}$ asymmetry at HERA energies was predicted in ref. [47] and it was also noted that the $p/\bar{p}$ asymmetry measured at HERA can be obtained by simple extrapolation of ISR data [48]. The quantitative description of the baryon number transfer due to SJ diffusion in rapidity space was obtained in [6] and following papers [6, 7, 8, 9, 10, 11].

In the QGSM the differences in the spectra of secondary baryons produced in the central region appear for processes which present SJ diffusion in rapidity space. These differences only vanish rather slowly when the energy increases.

To obtain the net baryon charge, and according to ref. [6], we consider three different possibilities. The first one is the fragmentation of the diquark giving rise to a leading baryon (Fig. 10a). A second possibility is to produce a leading meson in the first break-
up of the string and a baryon in a subsequent break-up \cite{37,49} (Fig. 10b). In these two first cases the baryon number transfer is possible only for short distances in rapidity. In the third case, shown in Fig. 10c, both initial valence quarks recombine with sea antiquarks into mesons $M$ while a secondary baryon is formed by the SJ together with three sea quarks.

![Diagram](image)

**Figure 10:** QGSM diagrams describing secondary baryon $B$ production by diquark $d$: initial SJ together with two valence quarks and one sea quark (a), initial SJ together with one valence quark and two sea quarks (b), and initial SJ together with three sea quarks (c).

The fragmentation functions for the secondary baryon $B$ production corresponding to the three processes shown in Fig. 10 can be written as follows (see \cite{6} for more details):

\[
G_{qq}^B(z) = a_N \cdot v_{qq} \cdot z^{2.5},
\]

\[
G_{qs}^B(z) = a_N \cdot v_{qs} \cdot z^2 \cdot (1 - z),
\]

\[
G_{ss}^B(z) = a_N \cdot \varepsilon \cdot v_{ss} \cdot z^{1 - \alpha_{SJ}} \cdot (1 - z)^2,
\]

for Figs. 10a, 10b, and 10c, respectively, and where $a_N$ is the normalization parameter, and $v_{qq}$, $v_{qs}$, $v_{ss}$ are the relative probabilities for different baryons production that can be found by simple quark combinatorics \cite{50,52}.

The fraction $z$ of the incident baryon energy carried by the secondary baryon decreases from Fig. 10a to Fig. 10c, whereas the mean rapidity gap between the incident and secondary baryon increases. The first two processes can not contribute to the inclusive spectra in the central region, but the third contribution is essential if the value of the intercept of the SJ exchange Regge-trajectory, $\alpha_{SJ}$, is large enough. At this point it is important to stress that since the quantum number content of the SJ exchange matches that of the possible Odderon exchange, if the value of the SJ Regge-trajectory intercept, $\alpha_{SJ}$, would turn out to be large and it would coincide with the value of the Odderon Regge-trajectory, $\alpha_{SJ} \simeq 0.9$, then the SJ could be identified to the Odderon, or to one baryonic Odderon component.
Let’s finally note that the process shown in Fig. 10c can be very naturally realized in the quark combinatorial approach [50] through the specific probabilities of a valence quark recombination (fusion) with sea quarks and antiquarks, the value of $\alpha_{SJ}$ depending on these specific probabilities.

The contribution of the graph in Fig. 10c has in QGSM a coefficient $\varepsilon$ which determines the small probability for such a baryon number transfer.

6 Comparison of the QGSM predictions with the experimental data

With the value $\alpha_{SJ} = 0.5$ used to obtain the first QGSM predictions [6] different values of $\varepsilon$ were needed for the correct description of the experimental data at moderate and high energies. A better solution was found in ref. [7], where it was shown that all experimental data can be described with the value $\alpha_{SJ} = 0.9$ and only one value of $\varepsilon$. This large value of $\alpha_{SJ}$ allows to describe the preliminary experimental data of H1 Collaboration [16] on asymmetry of $p$ and $\bar{p}$ production in $\gamma p$ interactions at HERA with a rather small change in the description of the data at moderate energies. A similar analysis presented in ref. [9] for midrapidity asymmetries of $\bar{\Lambda}/\Lambda$ produced in $pp$, $pA$, $\pi p$, and $ep$ interactions also shows that the value $\alpha_{SJ} = 0.9$ is slightly favoured, mainly due to the H1 Collaboration point [51].

Here we compare the results of QGSM predictions with all available experimental data on the $\bar{p}/p$ ratios presented in Fig. 5. To obtain these predictions we use the values of the probabilities $w_n$ in Eq. (15) that are calculated in the frame of Reggeon theory [33], and the values of the normalization constants $a_\pi$ (pion production), $a_K$ (kaon production), $a_{\bar{B}}$ ($B\bar{B}$ pair production), and $a_N$ (baryon production due to SJ diffusion) that were determined [33, 34, 35] from the experimental data at fixed target energies.

To compare the QGSM results obtained with different values of $\alpha_{SJ}$ in Eq. (26) all curves should be normalized at the same arbitrary point that we have chosen to be the experimental value of $\bar{p}/p$ ratio at $\sqrt{s} = 27.4$ GeV [28]. To do so it was necessary to slightly change the fragmentation function of $uu$ and $ud$ diquarks into secondary antiproton, which now has the form:

$$G^\bar{p}_{uu}(z) = G^\bar{p}_{ud}(z) = a_{\bar{N}} \cdot (1 - z)^{\lambda - a_R + 4(1 - a_B)} \cdot (1 + 3z), \quad (27)$$

with a smaller value of $a_{\bar{N}}$, $a_{\bar{N}} = 0.13$, and an additional factor $(1 + 3z)$ with respect to the expression in ref. [6]. For all other quark distributions and fragmentation functions
the same expressions as in ref. [6] have been taken. The quality of the description of the \( \bar{p} \) inclusive spectra with fragmentation function of Eq. (27) is shown to be even better than in previous papers (see Fig. 11).

The ratio of \( p \) to \( \bar{p} \) yields at \( y^* = 0 \) calculated with the QGSM is shown in the left panel of Fig. 12. The results with \( \alpha_{SJ} = 0.9 \) and \( \varepsilon = 0.024 \), \( \alpha_{SJ} = 0.6 \) and \( \varepsilon = 0.057 \), and \( \alpha_{SJ} = 0.5 \) and \( \varepsilon = 0.0757 \) are presented by dashed (\( \chi^2/\text{ndf}=21.7/10 \)), dotted (\( \chi^2/\text{ndf}=12.2/10 \)), and dash-dotted (\( \chi^2/\text{ndf}=11.1/10 \)) curves, respectively. Thus the most probable value of \( \alpha_{SJ} \) from the point of view of \( \chi^2 \) analyses is \( \alpha_{SJ} = 0.5 \pm 0.1 \).

The calculated ratios of \( \bar{p} \) to \( p \) yields as function of rapidity are shown in the right panel of Fig. 12. In accordance with the experimental conditions [29] we use here the value \( \langle p_T \rangle = 0.9 \) GeV/c both for secondary \( p \) and \( \bar{p} \). We also present here the calculations with \( \alpha_{SJ} = 0.9 \) and \( \varepsilon = 0.024 \), \( \alpha_{SJ} = 0.6 \) and \( \varepsilon = 0.057 \), and \( \alpha_{SJ} = 0.5 \) and \( \varepsilon = 0.0757 \) by dashed (\( \chi^2/\text{ndf}=72.8/10 \)), dotted (\( \chi^2/\text{ndf}=18.6/10 \)), and dash-dotted (\( \chi^2/\text{ndf}=17.0/10 \)) curves, the most probable value of \( \alpha_{SJ} \) being again \( 0.5 \pm 0.1 \).

7 Conclusion

The experimental data on the differences in particle and antiparticle total cross sections with a proton target have been considered in Section 2. As discussed there, a possible
Odderon contribution can be present in this case of \( \bar{p}p \) and \( pp \) total cross sections, while such an Odderon contribution should be significantly suppressed for \( K^-p \) and \( K^+p \) total cross sections and should turn out to be zero for \( \pi^-p \) and \( \pi^+p \) total cross sections. With the Odderon corresponding to a reggeized three-gluon exchange in \( t \)-channel this last feature appears naturally.

However one has to note that the possibility of an Odderon exchange contribution in \( \bar{p}p \) and \( pp \) is supported by the data of \( \bar{p}/p \) scattering obtained at ISR energies (\( \sqrt{s} \geq 30 \text{ GeV} \)), where not experimental data (at so high energies) for \( K^-p \) and \( K^+p \) exist.

On the other hand, the main part of experimental data for the ratios of real/imaginary parts of elastic \( pp \) amplitude, including the ISR data, are in agreement with absence of any Odderon contribution if the value of \( \alpha_{Odd} \) is close to one. The exceptions to this fact are the FNAL data \([19]\) and the oldest CERN-SPS experimental point \([21]\) that allows some room for the Odderon contribution to be present.

Thus it seems that the ISR data on the differences of particle and antiparticle total interaction cross sections and the data on the ratios of real/imaginary parts of elastic \( pp \) amplitude are not completely consistent with each other.

In the case of the inclusive production of particles and antiparticles in central (midrapidity) region in \( pp \) collisions we could not see any contribution by the Odd-
eron. All experimental data are consistent with a value $\alpha_R(0) \simeq 0.5$, a little larger than the conventional value of $\alpha_\omega(0) \simeq 0.4$, that is too small for the Odderon contribution to be there. On top of that, the energy for the possible Odderon exchange is $\sqrt{s} \simeq 15-20$ GeV, perhaps too small, since we did not saw any Odderon contribution at such energies in the case of the differences of particle and antiparticle total interaction cross sections, either. Actually, the only evidence for the Odderon exchange with $\alpha_{Odd}(0) \simeq 0.9$ are two experimental points for $\bar{B}B$ production asymmetry by the H1 Collaboration [16, 51]. The first point [16] (for $\bar{p}/p$ ratio) is until now not published, and the second one [51] (for $\bar{\Lambda}/\Lambda$ ratio) shows a very large error bar, but on the other hand only for these two points the kinematics would allow the energy of the Odderon exchange to be large enough, $\sqrt{s} \simeq 10^2$ GeV.

One has to expect that the LHC data will make the situation more clear. The QGSM predictions for the deviation of $\bar{B}/B$ ratios from unity due to SJ contribution with $\alpha_{SJ}(0) \simeq 0.9$ have been already published [11], and they allow deviations from unity on the level of 3-4%, while for smaller values of $\alpha_{SJ}(0)$ these ratios should be close to one.

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