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Helicity in proton–proton elastic scattering and the spin structure of the pomeron

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ABSTRACT

We discuss different models for the spin structure of the nonperturbative pomeron: scalar, vector, and rank-2 symmetric tensor. The ratio of single-helicity-flip to helicity-conserving amplitudes in polarised high-energy proton–proton elastic scattering, known as the complex r_5 parameter, is calculated for these models. We compare our results to experimental data from the STAR experiment. We show that the spin-0 (scalar) pomeron model is clearly excluded by the data, while the vector pomeron is inconsistent with the rules of quantum field theory. The tensor pomeron is found to be perfectly consistent with the STAR data.

1. Introduction

High-energy small-angle hadron–hadron scattering is dominated by the exchange of the soft pomeron. The nature of this pomeron has been discussed in a great number of articles; for reviews see, for instance, [1–4]. It is clear that it has vacuum internal quantum numbers. What is much less clear is the spin structure of the soft pomeron. Indeed, the present authors have frequently been asked the following question: The pomeron has vacuum quantum numbers, should it then not also have spin zero? However, a vector pomeron is widely used in the literature following [5–7]. In [8] it was proposed to describe the soft pomeron as an effective rank-2 symmetric tensor exchange. There, all reggeon exchanges with charge conjugation $C = +1$ ($C = -1$) were described as effective tensor (vector) exchanges and a large number of the couplings of these objects to hadrons were determined from experimental data. This tensor-pomeron model was then applied to various reactions in [9–13].

The authoritative answer to the question for the spin structure of the soft pomeron should be given by experiment. In this article we want to show that experimental data on the helicity structure of small-t proton–proton high-energy elastic scattering from the STAR experiment [14] indeed give decisive information on the spin structure of the soft pomeron.

We emphasise that in the following we shall be interested only in soft hadronic scattering where, according to standard wisdom, perturbative QCD methods cannot be applied.

2. Theoretical framework

We will consider pp elastic scattering

$$p(p_1, s_1) + p(p_2, s_2) \longrightarrow p(p_3, s_3) + p(p_4, s_4)\,, \tag{2.1}$$

where p_j are the four-momenta and $s_j \in \{1/2, -1/2\}$ the helicity indices, respectively. The standard kinematic variables are

$$\begin{aligned} s &= (p_1 + p_2)^2 = (p_3 + p_4)^2\,, \\ t &= (p_1 - p_3)^2 = (p_2 - p_4)^2\,, \\ u &= (p_1 - p_4)^2 = (p_2 - p_3)^2\,. \end{aligned} \tag{2.2}$$

At high energies, $s \gg m_p^2$, $|t|$, the reaction (2.1) is dominated by pomeron exchange; see Fig. 1. In the following all non-leading reggeon exchanges will be neglected. For $\sqrt{s} \geqslant 200$ GeV their contribution to the total cross section is only $\lesssim 1\%$ [1].

We shall test three hypotheses for the pomeron and the effective pomeron–proton–proton ($\mathbb{P}pp$) vertex. We shall treat the

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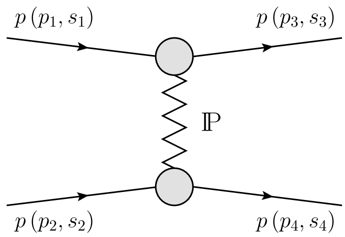


Fig. 1. Proton–proton elastic scattering via pomeron exchange.

pomeron either as a scalar, a vector, or a rank-2 symmetric tensor exchange. For all three cases it turns out to be possible to adjust the effective pomeron propagators and the couplings in such a way that at high energies the helicity-conserving pp amplitudes have the standard form as given in the vector-pomeron model due to Donnachie and Landshoff; see [5–7] and [1]. We will choose the parameters for the scalar and the tensor pomeron accordingly.

2.1. Tensor pomeron $\mathbb{P}_T$

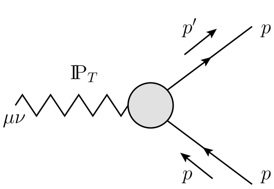
Here we describe the pomeron, as discussed in [8], as a symmetric, rank-two, tensor $\mathbb{P}_{T\mu\nu}(x)$ and its interaction with protons by coupling it to a tensor current $J_{T\mu\nu}(x)$,

$$\begin{aligned} &\mathcal{L}'_T(x) = J_{T\mu\nu}(x)\,\mathbb{P}_T^{\mu\nu}(x)\,, \\ &J_{T\mu\nu}(x) = -3\beta_{\mathbb{P}NN}\frac{i}{2}\bar{\psi}_p(x)\left[\gamma_\mu \overset{\leftrightarrow}{\partial_\nu} + \gamma_\nu \overset{\leftrightarrow}{\partial_\mu} - \frac{1}{2}g_{\mu\nu}\gamma^\lambda \overset{\leftrightarrow}{\partial_\lambda}\right]\psi_p(x); \end{aligned} \tag{2.3}$$

see (6.27) of [8]. Here $\psi_p(x)$ is the proton field operator and

$$3\beta_{\mathbb{P}NN} = 3\times 1.87\,\mathrm{GeV}^{-1} \tag{2.4}$$

is the standard coupling constant describing the pomeron–nucleon interaction; see [1,8]. From (2.3) we get the $\mathbb{P}_T pp$ vertex (see (3.43) of [8]) as[2]



$$\begin{aligned} &i\Gamma^{(\mathbb{P}_T pp)}_{\mu\nu}(p', p) \\ &= -i\,3\beta_{\mathbb{P}NN}F_1[(p'-p)^2]\bigg\{\frac{1}{2}\left[\gamma_\mu(p'+p)_\nu + \gamma_\nu(p'+p)_\mu\right] \\ &\quad -\frac{1}{4}g_{\mu\nu}(\not{p}'+\not{p})\bigg\}. \end{aligned} \tag{2.5}$$

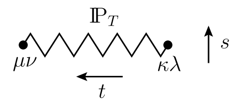
A form factor, $F_1(t)$, has been introduced in the vertex (2.5). Conventionally this is taken as the Dirac electromagnetic form factor of the proton, following [5–7]. The normalisation is

$$F_1(0) = 1\,. \tag{2.6}$$

In the sequel the precise form of $F_1(t)$ will not be relevant.

The ansatz for the effective $\mathbb{P}_T$ propagator is given in (3.10) and (3.11) of [8] and reads

[2] Note that from now on we will choose the orientation of the diagrams such that the t-channel is in horizontal and the s-channel in vertical direction.



$$\begin{aligned} &i\Delta^{(\mathbb{P}_T)}_{\mu\nu,\kappa\lambda}(s,t) \\ &= \frac{1}{4s}\left(g_{\mu\kappa}g_{\nu\lambda} + g_{\mu\lambda}g_{\nu\kappa} - \frac{1}{2}g_{\mu\nu}g_{\kappa\lambda}\right)(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}\,. \end{aligned} \tag{2.7}$$

We assume a standard linear form for the pomeron trajectory (see [1,8])

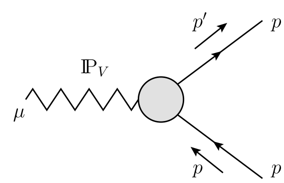
$$\begin{aligned} &\alpha_{\mathbb{P}}(t) = 1 + \epsilon_{\mathbb{P}} + \alpha'_{\mathbb{P}}t\,, \\ &\epsilon_{\mathbb{P}} = 0.0808\,, \\ &\alpha'_{\mathbb{P}} = 0.25\,\mathrm{GeV}^{-2}\,. \end{aligned} \tag{2.8}$$

2.2. Vector pomeron $\mathbb{P}_V$

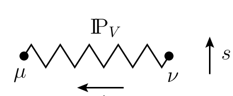
Here the pomeron has a vector index and is coupled to a vector current

$$\begin{aligned} &\mathcal{L}'_V(x) = J_{V\mu}(x)\,\mathbb{P}_V^\mu(x)\,, \\ &J_{V\mu}(x) = -3\beta_{\mathbb{P}NN}\,M_0\,\bar{\psi}_p(x)\gamma_\mu\psi_p(x)\,, \end{aligned} \tag{2.9}$$

where $M_0 \equiv 1$ GeV is introduced for dimensional reasons. The corresponding $\mathbb{P}_V pp$ vertex and $\mathbb{P}_V$ propagator are as follows (see (B.1) and (B.2) of [9]):



$$i\Gamma^{(\mathbb{P}_V pp)}_\mu(p', p) = -i\,3\beta_{\mathbb{P}NN}M_0F_1[(p'-p)^2]\,\gamma_\mu\,, \tag{2.10}$$



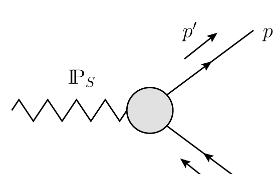
$$i\Delta^{(\mathbb{P}_V)}_{\mu\nu}(s,t) = \frac{1}{M_0^2}g_{\mu\nu}\,(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}\,. \tag{2.11}$$

2.3. Scalar pomeron $\mathbb{P}_S$

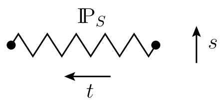
Finally, for comparison, we discuss also a scalar pomeron $\mathbb{P}_S$ coupled to a scalar current

$$\begin{aligned} &\mathcal{L}'_S(x) = J_S(x)\,\mathbb{P}_S(x)\,, \\ &J_S(x) = -3\beta_{\mathbb{P}NN}\,M_0\,\bar{\psi}_p(x)\psi_p(x)\,. \end{aligned} \tag{2.12}$$

Here we have as $\mathbb{P}_S pp$ coupling and as $\mathbb{P}_S$ propagator the following expressions:



$$i\Gamma^{(\mathbb{P}_S pp)}(p', p) = -i\,3\beta_{\mathbb{P}NN}M_0F_1[(p'-p)^2]\,, \tag{2.13}$$



$$i\Delta^{(\mathbb{P}_S)}(s,t) = \frac{s}{2m_p^2 M_0^2}\,(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}\,. \tag{2.14}$$

3. Helicity amplitudes

There are 16 helicity amplitudes for the reaction (2.1), defined as the $\mathcal{T}$-matrix elements

$$\begin{aligned}&\langle p(p_3,s_3), p(p_4,s_4)\,|\,\mathcal{T}\,|\,p(p_1,s_1), p(p_2,s_2)\rangle\\ &\quad\equiv \langle 2s_3, 2s_4\,|\,\mathcal{T}\,|\,2s_1, 2s_2\rangle\,,\\ &s_j \in \{1/2, -1/2\}, \quad j=1,\dots,4\,.\end{aligned} \tag{3.1}$$

The standard references for the general analysis of these amplitudes are [15–17]; see also [18]. Using rotational, parity (P), and time reversal (T) invariance, and taking into account that protons are fermions one finds that only five out of the 16 helicity amplitudes (3.1) are independent. Conventionally these are taken as

$$\begin{aligned}\phi_1(s,t) &= \langle ++\,|\,\mathcal{T}\,|\,++\rangle\,,\\ \phi_2(s,t) &= \langle ++\,|\,\mathcal{T}\,|\,--\rangle\,,\\ \phi_3(s,t) &= \langle +-\,|\,\mathcal{T}\,|\,+-\rangle\,,\\ \phi_4(s,t) &= \langle +-\,|\,\mathcal{T}\,|\,-+\rangle\,,\\ \phi_5(s,t) &= \langle ++\,|\,\mathcal{T}\,|\,+-\rangle\,.\end{aligned} \tag{3.2}$$

The amplitudes with no helicity flip are ϕ_1 and ϕ_3, with single flip ϕ_5, and with double flip ϕ_2 and ϕ_4. Our normalisation is such that the differential cross section for unpolarised protons is

$$\begin{aligned}\frac{d\sigma(pp\to pp)}{dt} &= \frac{1}{16\pi s(s-4m_p^2)}\frac{1}{4}\sum_{s_1,\dots,s_4}|\langle 2s_3,2s_4\,|\,\mathcal{T}\,|\,2s_1,2s_2\rangle|^2\\ &= \frac{1}{32\pi}\frac{1}{s(s-4m_p^2)}\Big\{|\phi_1(s,t)|^2+|\phi_2(s,t)|^2\\ &\quad+|\phi_3(s,t)|^2+|\phi_4(s,t)|^2+4\,|\phi_5(s,t)|^2\Big\}\,.\end{aligned} \tag{3.3}$$

The total cross section for unpolarised protons is[3]

$$\begin{aligned}\sigma_{\text{tot}}(pp) &= \frac{1}{\sqrt{s(s-4m_p^2)}}\frac{1}{4}\sum_{s_1,s_2}\text{Im}\,\langle 2s_1,2s_2\,|\,\mathcal{T}\,|\,2s_1,2s_2\rangle\,|_{t=0}\\ &= \frac{1}{2\sqrt{s(s-4m_p^2)}}\,\text{Im}\,[\phi_1(s,0)+\phi_3(s,0)]\,.\end{aligned} \tag{3.4}$$

Now it is straightforward to calculate the amplitudes $\phi_j(s,t)$ in the tensor-, vector-, and scalar-pomeron models of section 2. We use the phase conventions for the proton spinors of definite helicity as given in (4.10) of [15] and find the following results.

Tensor pomeron

$$\begin{aligned}&i\,\langle 2s_3,2s_4\,|\,\mathcal{T}\,|\,2s_1,2s_2\rangle\\ &\quad= i\big\langle p(p_3,s_3)\,\big|\,J_{T\mu\nu}(0)\,\big|\,p(p_1,s_1)\big\rangle\, i\Delta^{(\mathbb{P}_T)\mu\nu,\kappa\lambda}(s,t)\\ &\qquad\times i\,\langle p(p_4,s_4)\,|\,J_{T\kappa\lambda}(0)\,|\,p(p_2,s_2)\rangle\,,\\ &\big\langle p(p',s')\,\big|\,J_{T\mu\nu}(0)\,\big|\,p(p,s)\big\rangle = \bar{u}(p',s')\,\Gamma^{(\mathbb{P}_T pp)}_{\mu\nu}(p',p)\,u(p,s)\,.\end{aligned} \tag{3.5}$$

[3] We note that the amplitudes $\phi_j^{\text{BGL}}(s,t)$ defined in [16] are related to ours by $\phi_j^{\text{BGL}}(s,t) = \phi_j(s,t)/(8\pi)$.

Table 1
Results for the reduced pp scattering amplitudes $\hat{\phi}_j$ (3.7), $j=1,\dots,5$, for the tensor-, vector-, and scalar-pomeron ansätze. Terms of relative order m_p^2/s and $|t|/s$ are neglected.

	pomeron ansatz		
	tensor	vector	scalar
$\hat{\phi}_1(s,t)$	$8\ s^2$	$8\ s^2$	$8\ s^2$
$\hat{\phi}_2(s,t)$	$10\ m_p^2 t$	$16\ m_p^2 t$	$2\ s^2 t/m_p^2$
$\hat{\phi}_3(s,t)$	$8\ s^2$	$8\ s^2$	$8\ s^2$
$\hat{\phi}_4(s,t)$	$-10\ m_p^2 t$	$-16\ m_p^2 t$	$-2\ s^2 t/m_p^2$
$\hat{\phi}_5(s,t)$	$-8\ s m_p\sqrt{-t}$	$-8\ s m_p\sqrt{-t}$	$-4\ s^2\sqrt{-t}/m_p$

Inserting here the expressions from (2.5) and (2.7) we get the amplitudes $\phi_j(s,t)$. It is convenient to pull out a common factor

$$\begin{aligned}\mathcal{F}(s,t) &= i\,[3\beta_{\mathbb{P}NN}F_1(t)]^2\,\frac{1}{4s}(-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}\\ &= [3\beta_{\mathbb{P}NN}F_1(t)]^2\,\frac{1}{4s}(s\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1}\\ &\quad\times\left[\sin\left(\frac{\pi}{2}(\alpha_{\mathbb{P}}(t)-1)\right)+i\cos\left(\frac{\pi}{2}(\alpha_{\mathbb{P}}(t)-1)\right)\right]\end{aligned} \tag{3.6}$$

and to define reduced amplitudes by

$$\hat{\phi}_j(s,t) = \phi_j(s,t)/\mathcal{F}(s,t)\,, \qquad j=1,\dots,5. \tag{3.7}$$

The results for $\hat{\phi}_j(s,t)$ in the tensor-pomeron model are given in the column 'tensor' of Table 1. Terms of relative order m_p^2/s and $|t|/s$ are neglected.

Vector pomeron

$$\begin{aligned}&i\,\langle 2s_3,2s_4\,|\,\mathcal{T}\,|\,2s_1,2s_2\rangle\\ &\quad= i\big\langle p(p_3,s_3)\,\big|\,J_{V\mu}(0)\,\big|\,p(p_1,s_1)\big\rangle\; i\Delta^{(\mathbb{P}_V)\mu\nu}(s,t)\\ &\qquad\times i\,\langle p(p_4,s_4)\,|\,J_{V\nu}(0)\,|\,p(p_2,s_2)\rangle\,,\\ &\big\langle p(p',s')\,\big|\,J_{V\mu}(0)\,\big|\,p(p,s)\big\rangle = \bar{u}(p',s')\,\Gamma^{(\mathbb{P}_V pp)}_{\mu}(p',p)\,u(p,s)\,.\end{aligned} \tag{3.8}$$

Inserting here the expressions from (2.10) and (2.11) we get the reduced amplitudes $\hat{\phi}_j(s,t)$ (3.7) in the column 'vector' of Table 1.

Scalar pomeron

$$\begin{aligned}&i\,\langle 2s_3,2s_4\,|\,\mathcal{T}\,|\,2s_1,2s_2\rangle\\ &\quad= i\,\langle p(p_3,s_3)\,|\,J_S(0)\,|\,p(p_1,s_1)\rangle\; i\Delta^{(\mathbb{P}_S)}(s,t)\\ &\qquad\times i\,\langle p(p_4,s_4)\,|\,J_S(0)\,|\,p(p_2,s_2)\rangle\,,\\ &\big\langle p(p',s')\,\big|\,J_S(0)\,\big|\,p(p,s)\big\rangle = \bar{u}(p',s')\,\Gamma^{(\mathbb{P}_S pp)}(p',p)\,u(p,s)\,.\end{aligned} \tag{3.9}$$

Inserting here the expressions from (2.13) and (2.14) we get the reduced amplitudes $\hat{\phi}_j(s,t)$ (3.7) in the column 'scalar' of Table 1.

Let us now discuss the question whether our amplitudes should obey the so-called Regge factorisation which, according to standard lore, should hold for amplitudes governed by a single Regge-pole exchange; see for instance chapter 6.8g of [19]. In our case, Regge factorisation would require

$$\begin{aligned}&\langle 2s_3,2s_4\,|\,\mathcal{T}\,|\,2s_1,2s_2\rangle\,\big\langle 2s'_3,2s'_4\,\big|\,\mathcal{T}\,\big|\,2s'_1,2s'_2\big\rangle\\ &\quad= \big\langle 2s_3,2s'_4\,\big|\,\mathcal{T}\,\big|\,2s_1,2s'_2\big\rangle\big\langle 2s'_3,2s_4\,\big|\,\mathcal{T}\,\big|\,2s'_1,2s_2\big\rangle\\ &\quad= \big\langle 2s'_3,2s_4\,\big|\,\mathcal{T}\,\big|\,2s'_1,2s_2\big\rangle\big\langle 2s_3,2s'_4\,\big|\,\mathcal{T}\,\big|\,2s_1,2s'_2\big\rangle\end{aligned} \tag{3.10}$$

for any s_i, s'_j. It is straightforward to deduce the conditions which the amplitudes ϕ_j from (3.2) would have to fulfil for (3.10) to hold. These are

$$\begin{aligned}\phi_1(s,t) &= \phi_3(s,t)\,,\\ \phi_2(s,t) &= -\phi_4(s,t)\,,\end{aligned} \tag{3.11}$$

and

$$\phi_1(s,t)\phi_2(s,t) = -\phi_5(s,t)\phi_5(s,t)\,. \tag{3.12}$$

From Table 1 we see that the relations (3.11) are satisfied by all three pomeron models whereas (3.12) is only satisfied by the scalar-pomeron model. How can we understand this?

In all three of our models the amplitudes (3.1) have the structure

$$\begin{aligned}&\langle 2s_3, 2s_4\,|\,\mathcal{T}\,|\,2s_1, 2s_2\rangle\\ &\quad\propto (\text{vertex factor } v)^{(3,1)}(\mathbb{P}\text{ propagator})(\text{vertex factor } v)^{(4,2)},\end{aligned} \tag{3.13}$$

where the superscripts refer to the particle labels. For the scalar pomeron $\mathbb{P}_S$ this leads to

$$\langle 2s_3, 2s_4\,|\,\mathcal{T}\,|\,2s_1, 2s_2\rangle \propto v^{(3,1)}_{\mathbb{P}_S} v^{(4,2)}_{\mathbb{P}_S}. \tag{3.14}$$

That is, the amplitudes are proportional to a single product of two vertex factors. Clearly, in this case the factorisation relations (3.10) will hold, as we also see from Table 1. For a vector pomeron $\mathbb{P}_V$ and a tensor pomeron $\mathbb{P}_T$, on the other hand, we get

$$\langle 2s_3, 2s_4\,|\,\mathcal{T}\,|\,2s_1, 2s_2\rangle \propto v^{(3,1)}_{\mathbb{P}_V\mu} v^{\mu(4,2)}_{\mathbb{P}_V} \tag{3.15}$$

and

$$\langle 2s_3, 2s_4\,|\,\mathcal{T}\,|\,2s_1, 2s_2\rangle \propto v^{(3,1)}_{\mathbb{P}_T\mu\nu} v^{\mu\nu(4,2)}_{\mathbb{P}_T}, \tag{3.16}$$

respectively. Now the amplitudes are given by *sums* of products where, in general, the relations (3.10) will *not* hold.

We conclude that even if amplitudes are governed by a single Regge-pole exchange the Regge factorisation relations will not necessarily hold if the spin carried by the reggeon is taken into account. This remark applies not only to our tensor pomeron but, for instance, also to the ρ and ω reggeons which are considered as effective vector exchanges in [8]. We further note that also single-photon exchange in pp elastic scattering does not satisfy the relations (3.10). This can be seen explicitly from Table 1: For single-photon exchange, keeping only the Dirac form factor of the proton, the corresponding amplitudes are proportional to the entries of the column 'vector' where (3.12) is not satisfied.

4. Discussion and comparison with experiment

We note first that, by construction, the non-flip amplitudes $\phi_1(s,t)$ and $\phi_3(s,t)$ are the same for all three pomeron hypotheses. Thus, from (3.4), we get the same total cross section

$$\sigma_{\rm tot}(pp) = 2\,(3\beta_{\mathbb{P}NN})^2 \cos\left(\frac{\pi}{2}(\alpha_{\mathbb{P}}(0)-1)\right)\left(s\alpha'_{\mathbb{P}}\right)^{\alpha_{\mathbb{P}}(0)-1}\,. \tag{4.1}$$

This is the standard expression for the soft-pomeron contribution to $\sigma_{\rm tot}(pp)$; see [1] and (6.41) of [8].

Now we consider the vector-pomeron case. There, big problems arise if we consider pp and $\bar{p}p$ scattering. For $\bar{p}p$ elastic scattering we get an expression analogous to (3.8),

$$\begin{aligned}&i\,\langle \bar{p}(p_3,s_3), p(p_4,s_4)\,|\,\mathcal{T}\,|\,\bar{p}(p_1,s_1), p(p_2,s_2)\rangle\\ &\quad= i\big\langle \bar{p}(p_3,s_3)\,\big|\,J_{V\mu}(0)\,\big|\,\bar{p}(p_1,s_1)\big\rangle\, i\Delta^{(\mathbb{P}_V)\mu\nu}(s,t)\\ &\quad\quad\times i\,\langle p(p_4,s_4)\,|\,J_{V\nu}(0)\,|\,p(p_2,s_2)\rangle\,.\end{aligned} \tag{4.2}$$

A charge-conjugation transformation C gives

$$\begin{aligned}&\big\langle \bar{p}(p_3,s_3)\,\big|\,J_{V\mu}(0)\,\big|\,\bar{p}(p_1,s_1)\big\rangle\\ &\quad= -\big\langle p(p_3,s_3)\,\big|\,J_{V\mu}(0)\,\big|\,p(p_1,s_1)\big\rangle\,,\end{aligned} \tag{4.3}$$

as follows from the standard C-transformation rules of the (anti)proton states and of the bilinear expression for the vector current in terms of the proton fields (2.9). Thus, we get for a vector pomeron

$$\begin{aligned}&\langle \bar{p}(p_3,s_3), p(p_4,s_4)\,|\,\mathcal{T}\,|\,\bar{p}(p_1,s_1), p(p_2,s_2)\rangle\\ &\quad= -\langle p(p_3,s_3), p(p_4,s_4)\,|\,\mathcal{T}\,|\,p(p_1,s_1), p(p_2,s_2)\rangle\end{aligned} \tag{4.4}$$

and hence from (3.4)

$$\sigma_{\rm tot}(\bar{p}p) = -\sigma_{\rm tot}(pp)\,. \tag{4.5}$$

Clearly, this result does not make sense for a non-vanishing cross section and would contradict the rules of quantum field theory. Thus, we shall not consider a vector pomeron any further.[4]

We are left with the tensor- and scalar-pomeron hypotheses. We note that the C transformation here gives (see (2.3) and (2.12))

$$\begin{aligned}&\big\langle \bar{p}(p_3,s_3)\,\big|\,J_{T\mu\nu}(0)\,\big|\,\bar{p}(p_1,s_1)\big\rangle\\ &\quad= \big\langle p(p_3,s_3)\,\big|\,J_{T\mu\nu}(0)\,\big|\,p(p_1,s_1)\big\rangle\,,\end{aligned} \tag{4.6}$$

and

$$\langle \bar{p}(p_3,s_3)\,|\,J_S(0)\,|\,\bar{p}(p_1,s_1)\rangle = \langle p(p_3,s_3)\,|\,J_S(0)\,|\,p(p_1,s_1)\rangle\,. \tag{4.7}$$

This implies in both cases the equality of the pomeron contributions to the pp and $\bar{p}p$ scattering amplitudes, as should be the case.

In order to discriminate between the tensor and scalar pomeron cases we turn to data from the STAR experiment at RHIC [14]. There, a measurement of the ratio of single-flip to non-flip amplitudes at $\sqrt{s} = 200\,\text{GeV}$ was performed. The relevant quantity is

$$r_5(s,t) = \frac{2m_p\,\phi_5(s,t)}{\sqrt{-t}\,\text{Im}\,[\phi_1(s,t)+\phi_3(s,t)]}\,. \tag{4.8}$$

From (3.6), (3.7) and Table 1 we find for the tensor pomeron

$$r_5^{\mathbb{P}_T}(s,t) = -\frac{m_p^2}{s}\left[i + \tan\left(\frac{\pi}{2}(\alpha_{\mathbb{P}}(t)-1)\right)\right]. \tag{4.9}$$

For the scalar pomeron, on the other hand, we get

$$r_5^{\mathbb{P}_S}(s,t) = -\frac{1}{2}\left[i + \tan\left(\frac{\pi}{2}(\alpha_{\mathbb{P}}(t)-1)\right)\right]. \tag{4.10}$$

The measurement of r_5 in [14] is done for $0.003 \leqslant |t| \leqslant 0.035\,\text{GeV}^2$ and no t-dependence of r_5 is observed in this range. The latter observation is in agreement with our results (4.9) and (4.10) which also imply only a weak t-dependence of $r_5(s,t)$. Therefore, we can approximately set $t=0$ in (4.9) and (4.10) and obtain with $\sqrt{s} = 200\,\text{GeV}$

$$r_5^{\mathbb{P}_T}(s,0) = (-0.28 - i\,2.20)\times 10^{-5}\,, \tag{4.11}$$

$$r_5^{\mathbb{P}_S}(s,0) = -0.064 - i\,0.500\,. \tag{4.12}$$

It is worth pointing out that in the high-energy limit ($s \gg m_p^2$) these results have very small remaining uncertainties since only

[4] Let us remark here, however, that for proton–proton scattering the parameter r_5 discussed below would be the same in the vector-pomeron case as in the tensor-pomeron case as can be inferred from the amplitudes in Table 1.

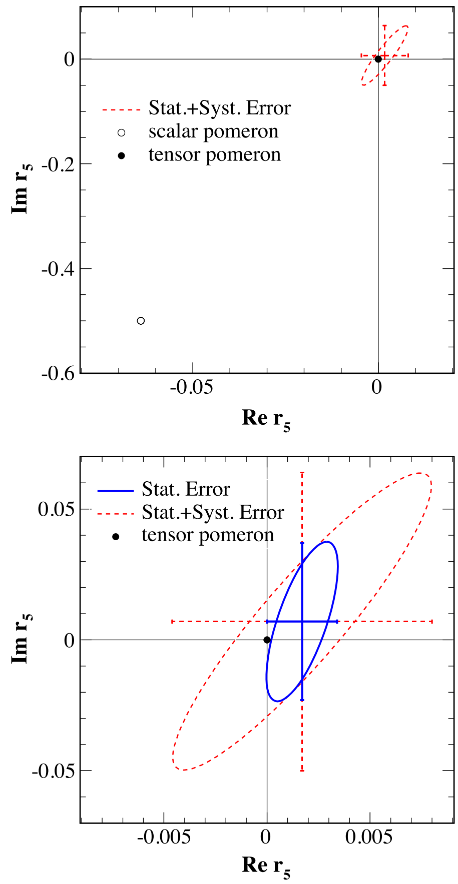


Fig. 2. The experimental results for r_5 at $\sqrt{s} = 200$ GeV from Fig. 5 of [14] together with our results for the tensor and the scalar pomeron; see (4.11) and (4.12). The first figure shows the experimental data together with the results for both pomeron models. The second figure shows a magnified view of the relevant region around zero and contains only the clearly favoured tensor-pomeron point.

the pomeron intercept $\alpha_{\mathbb{P}}(0)$ enters which is rather well determined experimentally. However, as the result (4.11) for the tensor pomeron is very small in absolute terms, it is conceivable that in this case subleading terms might be relevant for a calculation of r_5 with very high precision. But as we will see momentarily, the current experimental uncertainty does not allow a determination of r_5 to that precision anyway.

In Fig. 2 we show the experimental result for r_5 of [14] (as given in Fig. 5 there) together with our results (4.11) and (4.12). Clearly, the tensor-pomeron result is perfectly compatible with the experiment. The scalar-pomeron result, on the other hand, is far outside the experimental error ellipse. The tensor pomeron is hence strongly favoured by the data, while the scalar pomeron is ruled out.

5. Conclusions

In this article we have confronted three hypotheses for the soft pomeron – tensor, vector, and scalar – with experimental data on polarised high-energy pp elastic scattering from the STAR Collaboration [14]. Studying the ratio r_5 of single-helicity-flip to non-flip amplitudes we found that the STAR data are consistent with a tensor pomeron while they clearly exclude a scalar pomeron. We have further argued that a vector pomeron assumption is in contradiction to the rules of quantum field theory. We therefore conclude that the tensor pomeron is the only viable option.

Attempts to relate the pomeron to tensors were, in fact, already discussed in the 1960's [20–22]. In [20] the energy–momentum tensor was considered and from that and some further assumptions the ratio of meson–baryon to baryon–baryon cross sections was obtained giving, for instance,

$$\frac{\sigma_{\text{tot}}(\pi p)}{\sigma_{\text{tot}}(pp)} \approx \frac{m_K}{m_B} \approx \frac{1}{2}\,. \tag{5.1}$$

Here m_K and m_B are a mean meson mass, taken as the one of the K meson, and a mean baryon mass, respectively. This does not work phenomenologically, as in fact $\sigma_{\text{tot}}(\pi p)/\sigma_{\text{tot}}(pp) \approx 2/3$. Also, we cannot see the physics which would make the πp cross section proportional to the K mass.

In this connection we may discuss the consequences of the hypothesis that the tensor current $J_{T\mu\nu}(x)$ in (2.3) is proportional to the energy–momentum tensor with a *universal* constant of proportionality, independent of the hadron considered. It is easy to see that this leads to the same pomeron part of the total cross section for all hadron–hadron scatterings, for instance $\sigma(pp) = \sigma(\pi p) = \sigma(J/\psi\, p)$. Clearly, also this does not work phenomenologically. Our $J_{T\mu\nu}(x)$ in (2.3) *cannot* be universally proportional to the energy–momentum tensor.

In [21,22] attempts were made to relate the pomeron properties, in particular its couplings to hadrons, to those of tensor mesons of the $q\bar{q}$ type. However, with the advent of QCD and gluons it has become clear that the pomeron is a predominantly gluonic object; see the pioneering papers [23,24]. Thus, if one wants to relate the pomeron properties to mesonic ones it is natural to look for glueballs, and this, indeed, has been and is being done frequently. Here, one problem is that even today the status of glueballs is not particularly clear; for a review see [25]. A vast literature exists dealing with the pomeron in perturbative QCD, starting from the celebrated work [26,27]. Questions similar to those addressed in the present paper for the soft pomeron could be interesting also in the context of the perturbative pomeron, but this would be beyond the scope of the present paper.

For the soft pomeron phenomenology, for a long time then, a sort of vector pomeron was commonly used, following [5–7], although it was clear that this could not be completely correct due to the problems with charge conjugation explained in section 4. A first attempt to understand the soft pomeron in the framework of a toy model of nonperturbative QCD was made in [28]. In [29] functional integral techniques were used to analyse high-energy soft hadron–hadron scattering in QCD in a nonperturbative framework. It was shown in chapter 6 of [29] that the pomeron exchange can be understood as a coherent sum of exchanges of spin $2 + 4 + 6 + \ldots$. Going through the arguments there one can see that basically this structure is due to the helicity conserving fundamental quark–gluon coupling in QCD. In [8] a tensor pomeron was introduced which again can be viewed as a coherent sum of exchanges of spin $2 + 4 + 6 + \ldots$ (see appendix B of [8]) thus making contact with the considerations in QCD of [29]. We note that writing a regge exchange as a coherent sum of elementary spin exchanges goes back to [30]. Concerning specific experimental tests for the spin structure of the pomeron we should mention [31] where such tests were proposed for diffractive deep inelastic electron–proton scattering. Similar techniques were proposed in [32,33] for central production of meson resonances in pp collisions

$$p + p \longrightarrow p + \text{meson} + p\,. \tag{5.2}$$

In the light of our discussion here we cannot support the conclusions of [32,33] that the pomeron couples like a non-conserved vector current. In [9,11,12] the question of central production (5.2) was taken up again from the point of view of the tensor pomeron and it was shown that this does quite well in reproducing the data where available. It turned out, however, that central production with pomeron–pomeron fusion,

$$\mathbb{P} + \mathbb{P} \longrightarrow \text{meson}\,, \tag{5.3}$$

was not too sensitive to the nature of the pomeron, tensor or vector. But central production with fusion of a $C = -1$ object with the pomeron, e.g.

$$\gamma + \mathbb{P} \longrightarrow \pi^+ + \pi^- \tag{5.4}$$

is extremely sensitive to the nature of pomeron. For a tensor (vector) pomeron the $\pi^+\pi^-$ pair in (5.4) is in an antisymmetric (symmetric) state under the exchange $\pi^+ \leftrightarrow \pi^-$. Needless to say that since the pomeron has $C = +1$ the $\pi^+\pi^-$ pair in (5.4) must be in an antisymmetric state. Thus also from this point, a vector pomeron is excluded. Finally, also investigations of the pomeron using the AdS/CFT correspondence prefer a tensor nature for pomeron exchange [34,35].

According to the results for the helicity-amplitudes in polarised high-energy pp elastic scattering presented in this work the soft pomeron should be described as a rank-2 symmetric tensor exchange, as for example in the model of [8]. It is not a priori clear that the pomeron exhibits the same spin structure also in reactions involving high momentum transfers, i.e. reactions with the exchange of a hard (perturbative) pomeron. We would find it particularly desirable to study the spin structure of the pomeron in the interesting transition region between soft and hard reactions. It would therefore be useful to discuss further observables that are sensitive to the spin structure of the pomeron and that can be experimentally studied in a wide range of kinematic regimes.

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