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Reggeon, Pomeron and Glueball, Odderon-Hadron-Hadron Interaction at High Energies — From Regge Theory to Quantum Chromodynamics*

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Abstract *Based on analysis of scattering matrix S, and its properties such as analyticity, unitarity, Lorentz invariance, and crossing symmetry relation, the Regge theory was proposed to describe hadron-hadron scattering at high energies before the advent of QCD, and correspondingly a Reggeon concept was born as a mediator of strongly interaction. This theory serves as a successful approach and has explained a great number of experimental data successfully, which proves that the Regge theory can be regarded as a basic theory of hadron interaction at high energies and its validity in many applications. However, as new experimental data come out, we have some difficulties in explaining the data. The new experimental total cross section violates the predictions of Regge theory, which shows that Regge formalism is limited in its applications to high energy data. To understand new experimental measurements, a new exchange theory was consequently born and its mediator is called Pomeron, which has vacuum quantum numbers. The new theory named as Pomeron exchange theory which reproduces the new experimental data of diffractive processes successfully. There are two exchange mediators: Reggeon and Pomeron. Reggeon exchange theory can only produce data at the relatively lower energy region, while Pomeron exchange theory fits the data only at higher-energy region, separately. In order to explain the data in the whole energy region, we propose a Reggeon–Pomeron model to describe high-energy hadron-hadron scattering and other diffractive processes. Although the Reggeon–Pomeron model is successful in describing high-energy hadron-hadron interaction in the whole energy region, it is a phenomenological model. After the advent of QCD, people try to reveal the mystery of the phenomenological theory from QCD since hadron-hadron processes is a strong interaction, which is believed to be described by QCD. According to this point of view, we study the QCD nature of Reggeon and Pomeron. We claim that the Reggeon exchange is an exchange of multigluon,the color singlet gluon bound state. In particular, the Pomeron could be a Reggeized tensor glueball $\xi(2230)$ with mass of 2.23 GeV, quantum numbers $I^G, J^{PC} = 0^+, 2^{++}$ and decay width of about 100 MeV. The glueball exchange theory reproduces data quite well. Accordingly, we believe that the Odderon, consisting of three Reggeized gluons, and predicted by QCD, should also contribute to hadron-hadron scattering and many other diffractive processes. We search for the Odderon by studying $\bar{p}p$ and pp elastic scatterings at high energies. Our investigations on the differential cross section $d\sigma/dt$ of hadron-hadron scattering at various energies and comparisons with experimental data show that the Odderon plays an essential role in fitting to data. Therefore, we suggest that the measurements should be urgently done in order to confirm the existences of the Odderon and to test QCD.*

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Key words: hadron-hadron interaction, Regge theory, Reggeon and Pomeron, QCD, glueball and Odderon

1 Introduction

A microscopic understanding of hadron-hadron scattering remains an elusive goal of hadronic physics. This is unfortunate because the interaction of hadrons is of paramount importance from a variety of perspectives. At the hadronic level, it provides vital insight into the dynamics of quarks and gluons, and offers an opportunity to search for new physics and new particles such as quest for H-particle, Higgs, σ-meson, and the tensor glueball, Odderon. It is also relevant to the study of the quark-gluon plasma, since hadronic interactions can mask putative signals for the QCD phase transition. Applications extend beyond hadronic physics: for example, searching for CP-violating phases in the final states of D in B meson decay will require correctly accounting for strong interaction final state phases.[1] Of course, hadron-hadron interactions are directly relevant to a longstanding goal of nuclear physics, deriving the nuclear force from QCD. This issue is not just of intellectual concern since it is important to be able to extend our understanding of internuclear force to extreme conditions of temperature and pressure so that a variety of astrophysical and cosmological issues may be reliably examined.

High energy proton-proton (pp) and antiproton-proton ($\bar{p}p$) elastic scattering have been measured at CERN Intersecting Storage Rings (ISR)[2] and Super Proton Synchrotron (SPS) Collider,[3,4] and at Fermilab fixed target experiment,[5] and Tevatron experiment.[6,7] These experimental studies covering the center-of-mass (c.m.) energy range 23 to 62 GeV at ISR to 2 TeV at Tevatron will soon reach a new milestone when the Large Hadron Collider (LHC) at CERN comes into operation this year. At LHC, pp elastic differential cross section is planned to be measured at the unprecedented c.m. energy of 14 TeV by the experimental group TOTEM[8] (acronym for TORAL and Elastic measurement) in the momentum transfer range $|t| = 0$ to $|t| = 10$ GeV^2.

The importance of the field and experimental measurement with their resulting data have led to many theoretical models to describe these diffractive processes. Most of these models have focused on the region of $|t| = 0.5$ GeV^2.

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For example, (i) Single Pomeron exchange model[9] with trajectory $\alpha_p(t) = 1.08 + 0.25\ \mathrm{GeV}^{-2} \cdot t$; (ii) Multiple Pomeron exchange model with single and double diffractive dissociation;[10] (iii) Incident proton viewed as made up of two color dipoles in the target proton rest frame.[11]

The three groups have predicted pp elastic differential cross section $\mathrm{d}\sigma/\mathrm{d}t$ at LHC all the way from $|t| = 0$ to $|t| = 10\ \mathrm{GeV}^2$ on the basis of three different models: (i) Impact picture model based on the Cheng-Wu calculations of QCD tower diagrams;[12] (ii) Eikonalized Pomeron–Reggeon model using conventional Regge pole approach, but with multiple Pomeron, Reggeon exchanges included;[13] (iii) nucleon-structure model, where the nucleon has an outer cloud of quark-antiquark condensed ground state, an inner core of topological baryonic charge, and a still smaller quark-bag of valence quarks.[14,15] At the same time, a QCD-inspired Eikonalized model has also been proposed[16] to predict differential cross section $\mathrm{d}\sigma/\mathrm{d}t$ of pp elastic scattering at $\sqrt{s} = 14$ TeV and $|t| = 0 \sim 2.0\ \mathrm{GeV}^2$. This wide array of models attempting to describe pp elastic scattering at LHC reflects the view that quantitative understanding of this process will provide fundamental insight into the non-perturbative and the perturbative QCD dynamics.

It has been pointed out that the single Pomeron exchange model, where the leading singularity in the complex J-plane is given by a simple pole, could not provide the best fits to data for total cross sections, and for ratio ρ of the real to the imaginary part of the forward elastic scattering amplitude at whole energy range. This conclusion was based on an analysis of all available data at $t = 0$ for pp, $\bar{p}p$, $\pi^{\pm}p$, $K^{\pm}p$, γp and $\gamma\gamma$ scatterings, where three kinds of parameterizations were used: the first one is a triple-pole singularity which makes total cross sections rose as $\log^2(s)$ at high energies; the second is a double-pole singularity which produces total cross section σ_{tot} proportional to $\log(s)$, and the third is a simple-pole singularity which gives a power rise s^{ϵ}. The investigations concluded that the best fit was always given by the triple-pole Pomonon exchange, closely followed by the double pole, and that the simple-pole parametrization was excluded if one went down in energy to $\sqrt{s} = 5$ GeV or if one included the ρ parameter in the fit.

This article is organized as follows . In Sec. 2, we discuss Regge theory,[17] where the concepts of Reggeon and Pomeron are introduced and their applications to high energy hadron-hadron elastic scattering and other diffractive processes such as vector meson electro-production off the proton are briefly presented. Section 3 presents the gluonic origin and nature of Reggeon and Pomeron. That is, we discuss the origin and nature of Reggeon and Pomeron from QCD and claim the soft Pomeron could be a Reggeized tensor glueball $\xi(2230)$ with mass of 2.23 GeV, quantum numbers $I^G, J^{PC} = 0^+, 2^{++}$ and decay width of about 100 MeV. We strongly propose to search for the tensor glueball experimentally again. If tensor glueball existence as QCD predicted, the Odderon must present in nature. Therefore, searching for the existence of the Odderon is crucial not only for quest for new particle but also for testing QCD. In Sec. 4, we suggest the searching for the Odderon by studying $\bar{p}p$ and pp elastic scattering at high energies since the Odderon makes a big difference between the two different processes. Finally, section 5 devotes to summary and concluding remarks of this work.

2 Regge Theory and Reggeon, Pomeron

Before advent of Quantum Chromodynamics (QCD), we study hadron-hadron interaction by analyzing the S-matrix of the strong interaction process since we do not know how to describe the strongly interacting process theoretically. The analysis led us to a successful phenomenological theory called Regge theory.[17]

2.1 *Regge Theory and Reggeon*

The scattering amplitude of strongly interacting processes must satisfy the Lorentz invariance, analyticity and unitarity. These properties of the S-matrix of hadron-hadron scattering have led to the Regge theory[17] which describes high energy hadron-hadron interactions. The Regge theory is a successful description of hadronic dynamics at high energies, which investigates hadronic interaction by studying two hadron scatterings, $a + b \to c + d$. It relates the spin J and the mass M of a particle with the same internal quantum numbers[17] (strangeness, isospin, baryon number, etc.) by $J = \alpha_R\ (t = M^2)$. When one plots all known particles in the Chew–Frautschi plane (J vs. M^2) one sees that they all lie on a straight line called a Regge trajectory,[18]

$$\alpha_R(t) = \alpha_R(0) + \alpha'_R t\,. \tag{1}$$

where intercept $\alpha_R(0)$ is less than 1.0 ($\alpha_R(0) < 1.0$), and $\alpha'_R = 0.25\ \mathrm{GeV}^{-2}$. The particle that lies on the trajectory, Eq. (1), is called Reggeon. Therefore, in Regge theory, one exchange one or more trajectory and instead of speaking about a particle that is exchanged, one talks about a Reggeon exchange. The exchange of a Reggeon is equivalent to the exchange of many particles with different spins, the contribution of a single t-channel Regge pole to an s-channel helicity amplitude of the hadron-hadron elastic scattering is given[19] by

$$F^R_{\lambda_1\lambda_2;\lambda_3\lambda_4}(s,t) = R(s,t)\tau^R_{\lambda_1\lambda_2;\lambda_3\lambda_4}(t) \tag{2}$$

with

$$R(s,t) = \frac{1 + \xi_R \exp(-\mathrm{i}\pi\alpha_R(t))}{\sin(\pi\alpha_R(t))}\Big(\frac{s}{s_0}\Big)^{\alpha_R(t)}\,, \tag{3}$$

and

$$\tau^R_{\lambda_1\lambda_2;\lambda_3\lambda_4}(t) = g^R_{\lambda_1\lambda_3}(t)g^R_{\lambda_2\lambda_4}(t)\,, \tag{4}$$

where λ_i are the external particle helicities, $\xi_R = \pm 1$ is the Reggeon signature of partial wave, $\xi_R = +1$ is for crossing even and $\xi_R = -1$ for crossing odd. $\tau^R_{\lambda_1\lambda_3;\lambda_2\lambda_4}$ the residue function, $\alpha_R(t)$ the Regge trajectory given by Eq. (1) and s_0 is a constant scalar factor which is taken to be $s_0 = 1$ GeV from various references.[20] The expression of Eq. (2) can be diagrammatically represented by Fig. 1.

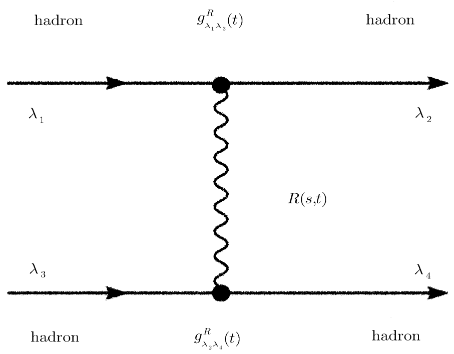

Fig. 1 The diagrammatical representation of hadron-hadron elastic scattering at high energies in Regge theory.

The most essential properties of the Reggeon exchange amplitude are the following, (i) All energy (s) dependence of the scattering amplitude $F_R(s,t)$ involves in the propagator-like factor $F^R_{\lambda_1\lambda_2;\lambda_3\lambda_4}(s,t)$ through the factor $s^{\alpha_R(t)}$; (ii) $F^R_{\lambda_1\lambda_2;\lambda_3\lambda_4}(s,t)$ is an analytic function of energy s and its phase is uniquely determined; (iii) $F^R_{\lambda_1\lambda_2;\lambda_3\lambda_4}(s,t)$ is even under the crossing transformation $s \rightleftharpoons u$ if the signature $\xi_R = +1$ and odd under the crossing transformation $s \rightleftharpoons -s$ if the signature $\xi_R = -1$; (iv) The most significant property of the residue function $\tau^R_{\lambda_1\lambda_2;\lambda_3\lambda_4}(t)$ is the factorization property as shown in Eq. (4), and figure 1 demonstrates the factorization explicitly. The presence of factorization provides analogy between Reggeon and Feynman diagrams as shown in Fig. 1.

The $R(s,t)$ plays the role of the Reggeon propagator, while residue functions, $\tau^R_{\lambda_1\lambda_2;\lambda_3\lambda_4}(t)$, stand for the usual vertex coupling interactions.[21] This analogy still is a deeper mystery because $R(s,t)$ has pole at t values where $\alpha_R(t)$ converts into an integer number. The Regge trajectory $\alpha_R(t)$ has the form as given in Eq. (1), where $\alpha_R(o) = 0.55$ and $\alpha'_R = 0.25$ GeV^{-2}, respectively. The vertexes $g^R_{ij}(t)$ are given[22] by

$$g^R_{ij}(t) = 3\beta_R\gamma^\mu F_1(t)\,, \tag{5}$$

with β_R being the Reggeon-hadron coupling strength given in Ref. [23]. The factor 3 in Eq. (5) comes from quark counting rule since there are three valence quarks inside the proton. $F_1(t)$ is the hadron isoscalar form factor given by[24]

$$F_1(t) = \frac{4m^2 - 2.8t}{4m^2 - t}(1 - 1.408t)^{-2}\,, \tag{6}$$

with m and t being hadron mass in units of GeV, and 4-momentum transfer in units of GeV^2, respectively. Given the Reggeon-nucleon coupling $g^R_{ij}(t)$, the amplitude of hadron-hadron scattering, for example pp elastic scattering, can be expressed as

$$T_{pp}(s,t) = \mathrm{i}\bar{u}(p_3)[3\beta_R\gamma^\mu F_1(t)]u(p_1)G_{pp}(s,t)\bar{u}(p_4)$$
$$\times\,[3\beta_R\gamma^\mu F_1(t)]u(p_2)\,, \tag{7}$$

where $u(p_i)$ is Dirac spinor of the proton and $G_{pp}(s,t)$ denotes the propagator of the Reggeon exchanged between the two vertices as shown in Fig. 1, and it is derived from Eq. (3) with a form

$$G_{pp}(s,t) = (-\mathrm{i}\alpha'_R s)^{\alpha_R(t)-1}\,. \tag{8}$$

After collecting all the ingredients together, the differential cross section, $\mathrm{d}\sigma/\mathrm{d}t$, is then given by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = \frac{[3\beta_R F_1(t)]^4(\alpha'_R s)^{2\alpha_R(t)-2}}{4\pi}\,, \tag{9}$$

and the total cross section, $\sigma_{\rm tot}(s)$, can be obtained from Eq. (7) by the optical theorem and has the form

$$\sigma_{\rm tot}(s) = \frac{2[3\beta_R F_1(0)]^2}{\sin(\alpha_R(0)/2)}[\alpha'_R s]^{\alpha_R(0)-1}\,. \tag{10}$$

Our theoretical prediction of the total cross section $\sigma_{\rm tot}(s)$ by use of Eq. (10) and Reggeon trajectory of Eq. (1) with the intercept $\alpha_R(0) = 0.55$, and slope $\alpha'_R = 0.25$ GeV^{-2} is shown in Fig. 2.

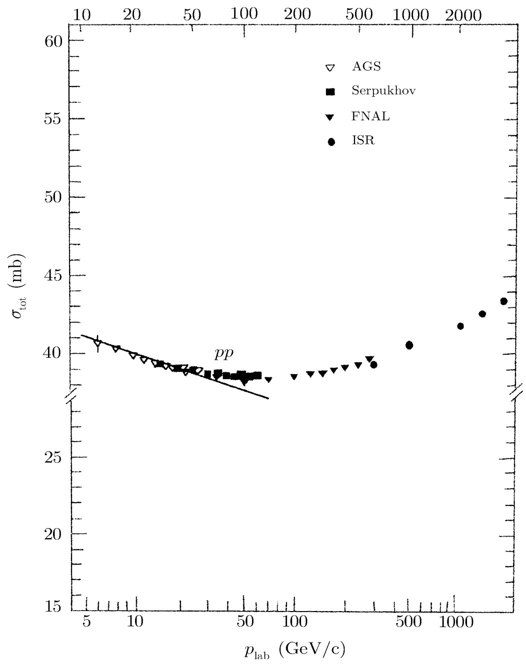

Fig. 2 Theoretical predictions of total cross section of high energy pp elastic scattering produced by Eq. (10) via the Reggeon exchange model with parameters $\alpha_R(0) = 0.55$, and $\alpha'_R = 0.25$ GeV^{-2}.

As is seen from Fig. 2, the Reggeon exchange model of Eq. (10) successfully reproduces low-energy pp elastic scattering data but it fails to describe the experimental data at high energies. The reason is that since $\alpha_R(0) = 0.55 < 1.0$, the exponent of s, $(\alpha_R(0) - 1)$ is negative. Therefore, as s increases to infinity, $[\alpha'_R s]^{\alpha_R(0)-1}$ approaches to zero. However, the new experimental measurements behave in an opposite way, as shown is Fig. 3. That is, the total cross sections do not vanish asymptotically but they rise slowly as s increases. Theoretical studies show that if we attribute this rising to exchange of a single Regge pole, then it follows that the exchange object must be of a Reggeon with intercept $\alpha_R(0)$ larger than 1.0.

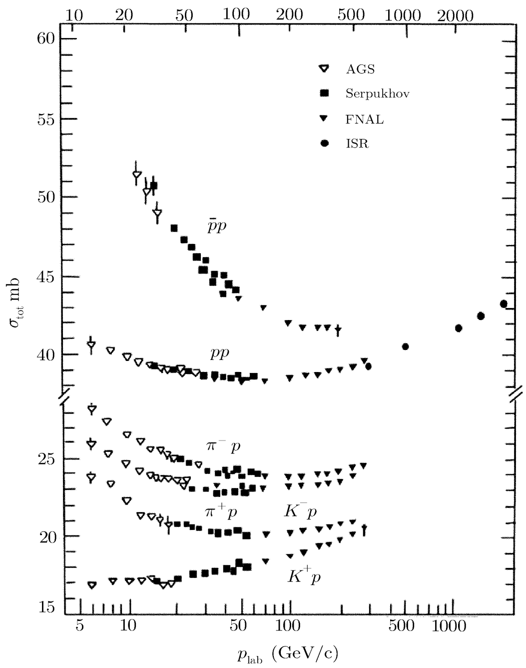

Fig. 3 The energy dependence of the experimental total cross section, $\sigma_{tot}(s)$, for pp, $\bar{p}p$, $\pi^{\pm}p$,and $K^{\pm}p$ elastic scattering at high energies.

2.2 *Pomeron and Pomeron Exchange Theory*

In order to explain the high energy experimental data of the total cross section from Regge theory, we introduce a new concept of the Pomeron. The new Reggeon with a trajectory

$$\alpha_P(t) = \alpha_P(0) + \alpha'_P t\,, \tag{11}$$

and its intercept $\alpha_P(0) \geq 1.0$ is called the Pomeron which is named after its inventor Pomeranchuck. The Pomeron must have vacuum quantum numbers: $I^G = 0^+$, $P = C = +1$ (I is isospin, G the G-parity, P parity and C-charge conjugation), since it has been proved that if for a particular scattering process the total cross section does not fall down as s increases, then that process must be dominated by the exchange of the vacuum quantum numbers[25] ($B = Q = S = I = 0$, $P = G = C = +1$).

The latest values of $\alpha_P(0)$ and α'_P are determined by experiments and they turned out[26] to be the following,

$$\alpha_P(0) = 1.08, \qquad \alpha'_P = 0.20\ \text{GeV}^{-2}\,. \tag{12}$$

Substituting the intercept of $\alpha_P(0) = 1.08$ and slope of $\alpha'_P = 0.20$ GeV^{-2} of the Pomeron trajectory, Eq. (11), into Eq. (10), we get the total cross section of high-energy pp elastic scattering in Pomeron exchange model as shown in Fig. 4.

Obviously, with $\alpha_P(0) = 1.08$ equation (10) leads to a slowly increasing of the total cross section as energy s increases, and thus it overcomes the difficulty faced by Reggeon exchange model in explaining the experimental data at high energies.

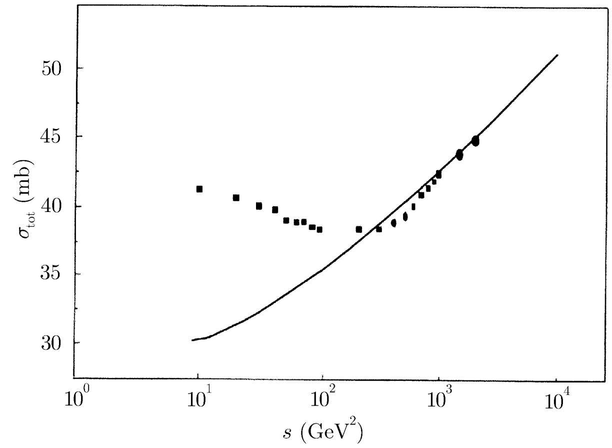

Fig. 4 Theoretical predictions of total cross section for proton-proton elastic scattering produced by Eq. (10) via the Pomeron exchange model with parameters $\alpha_P(0) = 1.08$, and $\alpha'_P = 0.20$ GeV^{-2}.

2.3 *Reggeon-Pomeron Exchange Model*

As is seen that the Pomeron exchange model cannot reproduce data at whole energy region, it only fits the data at higher energies. In order to fit experimental data at the whole energy region, we propose in this section a Reggeon–Pomeron exchange model to describe the pp elastic scattering by combining the contributions from Reggeon exchange and Pomeron exchange to the cross section.[9] Therefore, the total amplitude describing pp elastic scattering in the whole energy region should be conclusively

$$F_{R+P}(s,t) = F_R(s,t) + F_P(s,t)\,, \tag{13}$$

where $F_R(s,t)$ and $F_P(s,t)$ are the scattering amplitudes given by Reggeon exchange with trajectory $\alpha_R(t)$ of Eq. (1) and Pomeron exchange with trajectory $\alpha_P(t)$ in Eq. (11), respectively. Equation (13) is the detailed description of our Reggeon–Pomeron exchange model of high-energy hadron-hadron elastic scattering.

The calculations both for amplitudes $F_R(s,t)$ and $F_P(s,t)$ are quite same but using different trajectories, $\alpha_R(t)$ and $\alpha_P(t)$ for Reggeon and Pomeron, respectively. The numerical results of the Reggeon–Pomeron exchange model are shown in Fig. 5.

Inspecting Figs. 2, 4, and 5 strongly leads us to the following concluding remarks. (i) Reggeon exchange model with $\alpha_R(0) = 0.55$ and $\alpha'_R = 0.25$ GeV^{-2} can only reproduce the experimental data at the low energy region of $\sqrt{s} \leq 10$ GeV of total cross section $\sigma_{\text{tot}}(s)$; (ii) Pomeron exchange model with $\alpha_P(0) = 1.08$ and $\alpha'_P = 0.20$ GeV^{-2} just fits the experimental data well at higher energy region of $\sqrt{s}$ larger than several hundred GeV of total cross section $\sigma_{\text{tot}}(s)$; (iii) Our Reggeon–Pomeron exchange model given by Eq. (13) reproduces the experimental data successfully in the whole energy region where the experimental data exist.

However, unlike the Reggeon exchange, whose nature has been pointed out by many authors that the exchange of a Reggeon is equivalent to the exchange of many particles with different spins, the origin and nature of the Pomeron exchange in QCD are still unknown. In the next section, we shall study the origin and nature from the fundamental theory of QCD.

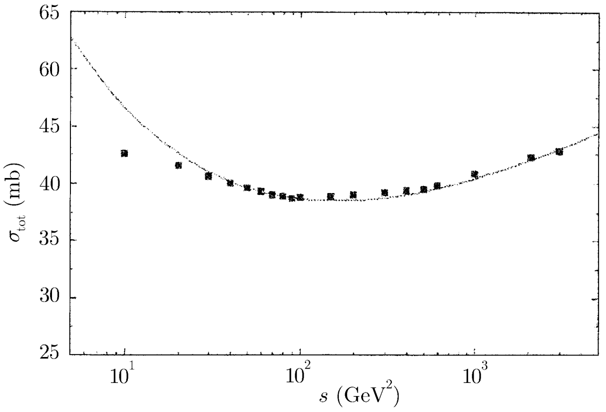

Fig. 5 Theoretical predictions of total cross section for pp elastic scattering produced by Eq. (13) via our Reggeon–Pomeron exchange model with parameters are as the same as those in Fig. 2, and Fig. 4, respectively.

3 Gluonic Origin and Glueball Nature of Reggeon and Pomeron

Since hadron-hadron scattering is a strong interaction process for which the mediators of force are gluons that interact among themselves. We exploit the gluonic origin and glueball nature of Reggeon and Pomeron in this section from QCD.

3.1 *QCD Origin and Multigluon Exchange Nature of the Reggeon*

Reggeons are the reggeized gluon colorless bound states and appear in the Regge limit where the square of the total energy s is large while the transfer of 4-momentum t is low and fixed ($s \to \infty$, $t \to$ const.) In this limit, the leading contribution to the scattering amplitude of hadrons is dominated by the exchange of intermediate particles, Reggeons, which are the compound states of gluons.[27] The Regge limit can be conveniently illustrated by considering the elastic scattering amplitudes of two-hadron scattering, $a(p_1) + b(p_2) \to c(p_3) + d(p_4)$ with (See Fig. 6)

$$s = (p_1 + p_2)^2, \qquad t = (p_1 - p_2)^2 \tag{14}$$

in the kinematical region:

$$s \to \infty, \qquad t = \text{const.} \tag{15}$$

In this case the largest contribution to the scattering amplitude is provided by a multi-gluon exchange as shown in Fig. 7. It was shown in Refs. [28] and [29] that in the limit of Eq. (15), the so-called gluon reggeization occurs. It means that the contribution to the scattering amplitude may be written as a sum of ladder diagrams, where compound states of the reggeized gluons, called Reggeons, are exchanged in the t-channel and interact with each other.

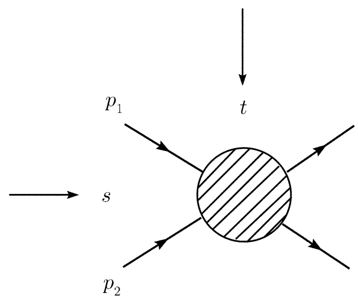

Fig. 6 Definition of the Mandemsteim variables,s, t, and u for two body interaction process $a(p_1) + b(p_2) \to c(p_3) + d(p_4)$.

In order to illustrate what the gluon reggeization is, we show in Fig. 7 some diagrams of the order g^4 and g^6 which give contributions to the total cross section $\sigma_{a+b\to c+d}(s)$ for two scattered hadrons. The Born approximation diagram, Fig. 7(a), appears in the lowest order of the perturbative calculations. Next diagrams, Figs. 7(b) and 7(c), are of the order g^6. They include virtual contributions and real gluon emission.

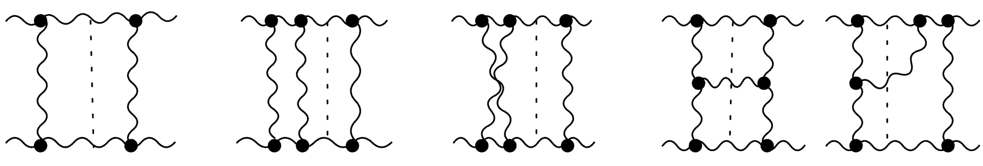

Fig. 7 Some diagrams of the order g_s^4 and g_s^6 which give contributions to the total cross section $\sigma_{a+b\to c+d}$. g_s is the strongly coupling constant of QCD.

Since gluon carries color the single gluon exchange between the two colliding hadrons is not possible due to the hadron is colorless object. The non-triviality of the virtual diagrams, due to the color factor, causes modification of gluon propagator. This phenomenon is called as gluon reggeization. A leading contribution in $\ln(s)$ coming from the diagrams of Fig. 7(b) type, i.e. of the order g^6, leads effectively to exchange of the gluon propagator,

$$\frac{1}{t} \to \frac{\omega(t)\ln(s)}{t}\,,$$
$$\omega(t) = 3\alpha_s t \int \frac{\mathrm{d}^2 l}{(2\pi)^2}\frac{1}{l^2(F_t - l)^2}\,. \tag{16}$$

Note that $\omega(t)$ in Eq. (16) is infrared-divergent. However, we perform regularization adding a small gluon mass. The summation of the leading terms obtained from the virtual diagrams gives

$$\frac{s^{\omega(t)}}{t}\,. \tag{17}$$

Similarly, the real gluon diagrams from Fig. 7(c) lead to the modification of vertices responsible for the gluon emission. Therefore, studying hadron-hadron scattering at high energies in QCD must calculate the contributions from various ladder diagrams in Fig. 7. In order to do so, we have to study the compound states of multigluons. This work is in progress.

3.2 *Gluonic Origin and Tensor Glueball Nature of Pomeron*

Since the Pomeron states have charge conjugation parity $C = +1$, we consider for simplicity purely perturbative gluon fields $A_\mu(x) = A_\mu^a(x)t^a$, where $t^a = \lambda^a/2$ are the generators of the gauge group $\mathrm{SU}(N_c)$ and x are coordinates of the gluon. Thus, under a charge conjugation transformation this field transforms as

$$A_\mu(x) \to -A_\mu^{\mathrm{T}}(x)\,, \tag{18}$$

where T denotes matrix transposition.

For $N = 2$ we have only one possibility to form a color singlet state from two gluon operators A_μ^a,

$$P_{\mu\nu}(x,y) = \mathrm{Tr}(A_\mu(x), A_\nu(y)) = \frac{1}{2}\delta_{ab}A_\mu^a(x)A_\nu^b(y)\,. \tag{19}$$

This state is invariant under charge conjugation Eq. (18), so that it has $C = +1$. Therefore, for two gluons we have only the Pomeron states. Accordingly, we may conclude that the Pomeron should be a reggeized tensor glueball $\xi(2230)$ with quantum numbers of I^G, $J^{PC} = 0^+, 2^{++}$, mass of 2.23 GeV, and decay width $\Gamma_\xi \simeq 100$ MeV. By use of this idea we have calculated the differential cross section and total cross section of pp elastic scattering at high energies.[21] The corresponding theoretical results of our calculations show that the tensor glueball must present in nature and has mass of 2.23 GeV, total decay width $\Gamma_\xi \simeq 100$ MeV (not 15 MeV as given by experiments[30]) with all quantum numbers of Pomeron, i.e, vacuum quantum numbers. Our calculated results also confirmed that the Pomeron could not be the Odderon since the Odderon has charge conjugation parity of $C = -1$, which is not consistent with vacuum quantum number $C = +1$, that the Pomenon must have.

3.3 *Odderon with Charge Conjugation Parity* $C = -1$

Odderon is a compound colorless state of three reggeized gluons with charge conjugation parity $C = -1$. For three reggeized gluons to form a singlet bound state, there are two ways of constructing a color singlet state. Firstly, one can build

$$\begin{aligned} P_{\mu\nu\rho}(x,y,z) &= -\mathrm{i}\,\mathrm{Tr}([A_\mu(x), A_\nu(y)]A_\nu(z)) \\ &= \frac{1}{2}f_{abc}A_\mu^a(x)A_\nu^b(y)A_\rho^c(z)\,, \end{aligned} \tag{20}$$

with the total antisymmetric structure constants f_{abc} defined via the Lie algebra of $\mathrm{SU}_c(3)$:

$$[t^a, t^a] = \mathrm{i} f_{abc}t^c\,. \tag{21}$$

Using Eq. (18), we find that $P_{\mu\nu\rho}(x,y,z)$ also have $C = +1$ structure. Therefore, for three reggeized gluon states, equation (20) gives a subleading correction to the two reggeized gluon bound states of the Pomeron.

The another possibility to form color singlet states is to use the totally symmetric constant

$$d_{abc} = 2[\,\mathrm{Tr}(t^a t^b t^c) + \mathrm{Tr}(t^c t^b t^a)]\,. \tag{22}$$

In this way, we obtain a state:

$$\begin{aligned} O_{\mu\nu\rho}(x,y,z) &= \mathrm{Tr}([A_\mu(x), A_\nu(y)]A_\rho(y)) \\ &= \frac{1}{2}d_{abc}A_\mu^a(x)A_\nu^b(y)A_\rho^c(z)\,. \end{aligned} \tag{23}$$

Similarly, applying Eq. (18) we find that equation (23) is odd under C-parity. Thus, it is the leading contribution to the Odderon state. This state only appears for the gauge groups $\mathrm{SU}_C(3)$ with reggeized gluon number larger than two.

In subsummary, since strong interaction of hadron-hadron scattering is described by QCD, the multigluon exchange must dominate the process, while in phenomenological description the process is explained successfully by Reggeon-Pomeron exchange. We claim that the contents of Reggeon and Pomeron must be gluonic: glueball, Odderon, and other color balls. We explicitly point out that the Pomeron could be tensor glueball $\xi(2230)$ with mass of 2.23 GeV, decay width about $\Gamma_\xi \simeq 100$ MeV, and quantum numbers $I^G, J^{PC} = 0^+, 2^{++}$ which has been observed by BES[30] and Mark-III [31] although it is still not confirmed experimentally. At the same time, the Odderon also contributes to hadron-hadron interaction. We discuss the contribution of the Odderon in the following section.

4 Searching for Odderon with $\bar{p}p$ and pp Elastic Scattering at High Energies

It has been concluded that the diffractive processes, the processes in which there are not any quantum number exchange between colliding particles,[32] proceed through exchanging Pomeron. The very successful and fundamental theory of strong interaction, QCD, and the experimental data of the large gaps of rapidity predict the existence of Pomeron, in the most simple version as a two-gluon exchange in color singlet state, thanks to the vector nature of the gluon. In fact, as we discussed in the previous section, the Pomeron is sum of colorless multi-reggeized gluon bound states with all properties that the Pomeron has. Since the Pomeron is described by a colorless bound state of interacting reggeized gluons in the t-channel, one can expect that the physical states on the Pomeron trajectory should be glueball states with largest spin. The lowest of these states is $J^{PC}=2^{++}$ glueball consisting of two constituent gluons with mass of 2.33 GeV, $\xi(2230)$. The fact that the internal gauge symmetry group of QCD has a rank greater than one permits to construct from three gluons a charge conjugation (C) odd state. Therefore, it is natural and necessary to consider the contributions from the three reggeized gluon bound states to the differential cross sections of hadron-hadron diffractive processes. The three-gluon bound state is a colorless object and called Odderon. The Odderon is defined phenomenologically as a singularity in the complex J-plane, located at $J=1$ when $t=0$ and which contributes to the odd-under-crossing amplitude $F_-(s,t)$.

4.1 *The Possible Existence of Odderon*

The concept of Odderon first emerged in 1973 in the context of asymptotic theorems.[33] Seven years later, it was possibly connected with 3-gluon exchanges in perturbative QCD (PQCD),[34] but it took seven years to firmly rediscover it in the context of PQCD.[35] The Odderon was also rediscovered recently in the color glass condensate (CGC) approach[36] and in the dipole picture.[37] One can therefore assert that the Odderon is a crucial test of QCD.

On experimental sector, there is a strong evidence for the non-perturbative Odderon: the discovery, in 1985, of a difference between $(\mathrm{d}\sigma/\mathrm{d}t)_{\bar{p}p}$ and $(\mathrm{d}\sigma/\mathrm{d}t)_{pp}$ in the dip-shoulder region $1.1\leq|t|\leq 1.5\ \mathrm{GeV}^2$ at $\sqrt{s}=52.8$ GeV.[38] Unfortunately, these data were obtained in one week just before ISR was closed and therefore the evidence, even if it is on a strong confidence level (99.9%), is not totally convincing. Moderate evidence for the existence of the non-perturbative Odderon also comes from the dramatic change of shape in the polarization in $\pi^-p\rightarrow\pi^0p$, in going from $P_L=5$ GeV[39] to $P_L=40$ GeV,[40] but this Odderon corresponds to a different type of Odderon as compared with the one identified in PQCD. Finally, weak evidence for the non-perturbative Odderon comes form a strange structure seen in the UA4/2 $\mathrm{d}N/\mathrm{d}t$ data for $\bar{p}p$ scattering at $\sqrt{s}=541$ GeV, namely a bump centered at $|t|=2.10^{-3}\ \mathrm{GeV}^2$.[41] This structure could correspond to oscillations of a very small period due to the presence of the Odderon.[42]

We search for the existence of Odderon by studying the differential cross sections of $\bar{p}p$ and pp elastic scattering at high energies and at moderate momentum transfer region of these diffractive processes.

4.2 *Odderon Exchange Theory and Its Formalism*

Let us now start our study from consideration of an elastic scattering process in the s-channel

$$a+b\rightarrow a+b \tag{24}$$

with the corresponding amplitude $F^{ab}(s,t)$. The amplitude of the related elastic scattering process in the u-channel

$$a+\bar{b}\rightarrow a+\bar{b} \tag{25}$$

with amplitude $F^{a\bar{b}}(s,t)$, can be obtained from the former, Eq. (24), by crossing to the u-channel, Eq. (25), via the crossing relation

$$F^{a\bar{b}}(s,t,u)=F^{ab}(u,t,s)\,. \tag{26}$$

We now define two new amplitudes $F_{\pm}$ by

$$F_{\pm}(s,t)=\frac{1}{2}[F^{ab}(s,t)\pm F^{a\bar{b}}(s,t)]\,. \tag{27}$$

Under the crossing from the s-channel process, Eq. (24), to the u-channel, Eq. (25), the amplitude $F_+(s,t)$ evidently remains unchanged whereas the amplitude $F_-(s,t)$ changes its sign. Accordingly, they are called even ($F_+(s,t)$) under-crossing-, and odd ($F_-(s,t)$) under-crossing amplitudes, respectively.

We observed that the amplitude $F_+(s,t)$ is the same for particle-particle and particle-antiparticle scatterings and thus corresponding to an exchange of even (or positive) C-party, $C=+1$. The amplitude $F_-(s,t)$ changes sigh when going from the particle-particle to the antiparticle-particle scattering process and can hence be understood to have odd (or negative) C-parity ($C=-1$). The amplitude $F_+(s,t)$ hence has vacuum quantum numbers, and we have already seen that it is dominated at high energy by the Pomeron exchange. It can be shown that the exchanges of the ρ or ω Reggeon trajectory are odd under crossing and hence contribute to the amplitude $F_-(s,t)$. The Odderon also contributes to the odd-under crossing amplitude $F_-(s,t)$ ($C=-1$). Taking $\bar{p}p$ and pp elastic scattering as an example to evaluate the role of Odderon in hadron-hadron scattering, we study $\bar{p}p$ and pp elastic scattering at high energies. From Eq. (27) we see that

$$F_{\pm}(s,t)=\frac{1}{2}[F_{pp}(s,t)\pm F_{\bar{p}p}(s,t)]\,, \tag{28}$$

which give us the $\bar{p}p$ and pp elastic scattering amplitudes defined by

$$F_{pp}(s,t)=F_+(s,t)+F_-(s,t) \tag{29}$$

and

$$F_{\bar{p}p}(s,t)=F_+(s,t)-F_-(s,t)\,. \tag{30}$$

Give scattering amplitude, the cross sections and the ratio of the real part to imaginary part of forward scattering amplitude are normalized such that

$$\sigma_{\mathrm{tot}}(s)=\frac{1}{s}\,\mathrm{Im}\,F(s,t=0)\,, \tag{31}$$

$$\rho(s)=\frac{\mathrm{Re}\,F(s,t=0)}{\mathrm{Im}\,F(s,t=0)}\,, \tag{32}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}=\frac{1}{16\pi s^2}|F(s,t)|^2\,, \tag{33}$$

According to Refs. [43] and [44], the amplitude $F_+(s,t)$ can be written as sum of the following components

$$F_+(s,t)=F_+^H(s,t)+F_+^P(s,t)+F_+^{PP}(s,t)+F_+^R(s,t)+F_+^{RP}(s,t)\,, \tag{34}$$

where $F_+^H(s,t)$ represents the contribution of a 3/2-cut collapsing at $t=0$, to a triple pole located at $J=$

1 and which satisfies the Auberson–Kinoshita–Martin asymptotic theorem,[43] $F_+^P(s,t)$ is the contribution of the Pomeron Regge pole, $F_+^{PP}(s,t)$ stands for the contribution of the Pomeron–Pomeron Regge cut, $F_+^R(s,t)$ is the contribution of a secondary Regge trajectory, whose intercept is located around $J = 1/2$ and associated with the $f_0(980)$ and $a_0(980)$ particles, $F_+^{RP}(s,t)$ notes the contribution of the Reggeon-Pomeron Regge-cut.

Correspondingly, the amplitudes $F_-(s,t)$ can be also written down as a sum of the following components

$$F_-(s,t) = F_-^{MO}(s,t) + F_-^O(s,t) + F_-^{OP}(s,t) + F_-^R(s,t) + F_-^{RP}(s,t)\,, \tag{35}$$

where $F_-^{\rm MO}(s,t)$ represents the maximal Odderon contribution which is based on the idea of a maximality principle for the strong interaction and has the behavior of the total cross section like $\sigma_{\rm tot} \to C\log^2(s)$ for $s \to \infty$ and a positive constant C, resulting from two complex conjugate pole collapsing at $t = 0$ to a dipole located at $J = 1$ and which satisfies the Haberson–Kinoshita-Martin asymptotic theorem,[44] $F_-^O(s,t)$ is the contribution of the minimal Odderon Regge pole, $F_-^{\rm OP}(s,t)$ stands for the contribution of the mininal Odderon–Pomeron Regge-cut, $F_-^R(s,t)$ is the contribution of a secondary Regge trajectory located around $J = 1/2$ and associated with the $\rho(790)$ and $\omega(782)$ particles, and finally, $F_-^{RP}(s,t)$ is the contribution of the Reggeon–Pomeron Regge-cut.

The explicit expressions of the individual terms in $F_+(s,t)$ and $F_-(s,t)$, Eqs. (35) and (36), are defined in our previous paper [45], respectively. Therefore, the observable $\sigma_{\rm tot}(s)$, $\rho(s,t)$ and $d\sigma/dt$ can be evaluated through equations in Ref. [45].

4.3 *Odderon Contribution to Differential Cross Section*

Our goal of this paper is to investigate the importance of Odderon contribution and to search for the existence of the Odderon in diffractive processes. We consider two cases, one in which the Odderon is absent and another one in which the Odderon is present. Let us first consider the case without the Odderon, that is, the case with $O_K = 0$ $(K = 1,2,3)$, $C_O = 0$, and $C_{Op} = 0$. Our theoretical predictions of differential cross section $d\sigma/dt$ for the pp and $\bar{p}p$ elastic scatterings at $\sqrt{s} = 52.8$ GeV are shown in Fig. 8.

As is seen from the Fig. 8, our model without Odderon contribution describes nicely the data in the momentum transfer region of $0 \le |t| \le 0.6\ {\rm GeV}^2$ but totally fails to describe the data for higher momentum transfer of t. This failure is not due to the absence of the odd-under-crossing amplitude, because, even if the Odderon contributions are absent, we still have the pole and cut contributions, $F_-^R(s,t)$ and $F_-^{RP}(s,t)$. However, these contributions fail to interfere with $F_+(s,t)$ contributions in a correct way, for two physically important reasons. One is that the fact that the intercept of the trajectory of the second Reggeon of odd signature is half a unit lower that the Pomeron pole intercept induces a fast decrease with the energy of the secondary Reggeon contributions and therefore the near equality of $\bar{p}p$ and pp differential cross section $d\sigma/dt$, in contrast with the data. Another reason is that the fact that the past phenomenology imposes universal numerical values of the slope $(\alpha'_R)^+$, $(\alpha'_R)^-$, and (α'_P), which are not free parameters, induces a decrease of $d\sigma/dt$ in t at fixed s and sufficiently high t, which is faster than what $d\sigma/dt$ data indicate. In particular, the moderate t region is very badly described. The values of the free parameters used in this calculation are given in our previous paper.[45]

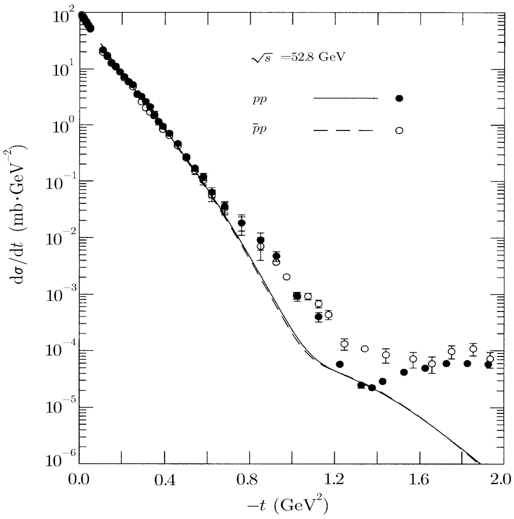

Fig. 8 Differential cross section $d\sigma/dt$ for pp and $\bar{p}p$ elastic scatterings at $\sqrt{s} = 52.8$ GeV without Odderon contribution. The solid line is for pp, while dashed line is for $\bar{p}p$ scattering. The full black circles and open circles are the corresponding experimental data for pp and $\bar{p}p$ elastic scatterings, respectively.

As has been pointed out by Ref. [46], the failure of the above considered amplitudes to describe the data in the moderate t region, does not mean that the failure of the Regge model. It simply means the need for the Odderon. The Regge pole model is justified not only by the existing data but also by the multitude of resonances present in review of particle physics,[47] which constitutes a striking evidence for linear Regge trajectory with universal slope. The Regge model has to be included as a basic ingredient in any more sophistical approach aiming to a realistic description of the experimental data. It is very encouraging that PQCD already gets Regge behavior, in particular, gluons are reggeized in PQCD.

Now, we turn to the second case with Odderon contribution. Our theoretical predictions of differential cross section $d\sigma/dt$ for pp and $\bar{p}p$ elastic scatterings at energy of $\sqrt{s} = 52.8$ GeV are shown in Fig. 9

By comparing Figs. 8 and 9, we can see the remarkable importance by including the Odderon contribution in describing the differential cross sections of $\bar{p}p$ and pp elastic scatterings at $\sqrt{s} = 52.8$ GeV. This difference fixes, in fact, as precisely as possible, the magnitude of the Odderon contribution. Our fit to data is very good within our best knowledge.

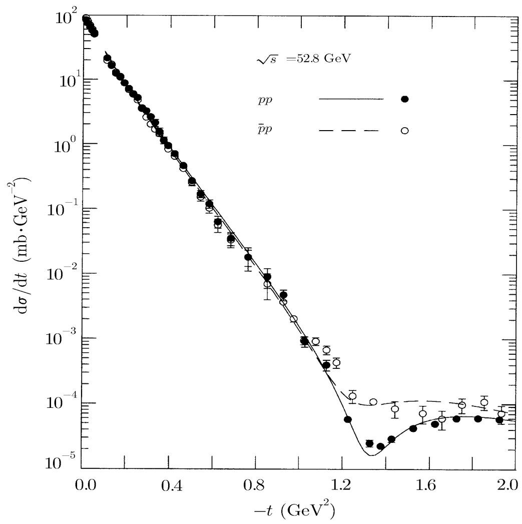

Fig. 9 Differential cross section $\mathrm{d}\sigma/\mathrm{d}t$ for $\bar{p}p$ and pp elastic scatterings at energy of $\sqrt{s} = 52.8$ GeV with Odderon contributions. The other explanations are the same as those in Fig. 8.

4.4 *Sub-summary and Sub-concluding Remarks*

It is remarkable that the QCD predicts the existence of the Odderon. The idea of the Odderon, the partner of the Pomeron, which is odd under parity P and charge conjugation C, is related to the possibility that the real part of a scattering amplitude increases with energy as fast as the imaginary part. The scattering amplitude in the complex angular momentum plane possesses a rightmost singularity (pole) near $J = 1$. In the even under crossing amplitude such a singularity is associated to the Pomeron and gives a mostly imaginary contribution, while in the odd case one has a mostly real contribution which is associated to the Odderon. The position of the singularity is also called intercept and it is related to the asymptotic behavior of the cross section.

Most models of diffractive scattering are constructed so that the crossing symmetric amplitude $F_+(s,t)$ dominates at high energies for all t[48]. The contributions to $F_-(s,t)$ are usually Regge-like and consequently have largely disappeared by ISR energies. Hence these models predict equality of $\bar{p}p$ and pp differential cross section, in serious contradiction with the ISR data at $\sqrt{s} = 52.8$ GeV. There are several models in the literature which include a crossing odd amplitude $F_-(s,t)$ that remains important at ISR energies. Between them, the most similar in spirit, as compared with our approach here, is the Donnachie–Landshoff (D-L) model,[48] which includes Odderon contribution, described as the exchange of 3 nonreggeized gluons, calculated in PQCD, and they include the Rogge poles and cuts contributions as an important component of their amplitudes. On a strictly theoretical level, there is no reason to apply PQCD in a moderate t-region on a phenomenological level, one has to note that D-L model does not well describe the pp and $\bar{p}p$ data at $\sqrt{s} = 52.8$ GeV in the critical structure region centered around $|t| = 1.35$ GeV^2. We think therefore that the existing data favor the maximal Odderon as compared with the D-L three-gluon Odderon.

There is no doubt about the theoretical evidence for the Odderon both in QCD and CGC. The Odderon is a fundamental object of these two approaches and it has to be found at RHIC and LHC if QCD and CGC are right. Our study and results in this section provide a good tool to search for the existence of the Odderon and to test QCD.

5 Conclusions

We study the hadron-hadron elastic scattering at high energies in terms of the Regge theory and the fundamental theory of strong interaction, QCD. That is, we analyze this process from the theory basing on phenomenological level and also from theory basing on quark-gluon dynamical level since the strong interaction is dominated by exchange of gluons. We believe that the Reggeon and/or Pomeron must relate to gluon exchange in hadron-hadron scattering. Therefore, we point out that the Reggeon simulates phenomenologically the summation of multigluon exchanges as is shown in Fig. 7. At the same time, we claim that the Pomeron could be a tensor gluoball with mass of 2.23 GeV, quantum numbers $I^G, J^{PC} = 0^+, 2^{++}$ and decay width $\Gamma_\xi \simeq 100$ MeV. The glueball has been observed by BES and Mark-III in 1996 and 1985, although some other experiment groups did not confirm the existence of the tensor glueball, even if the QCD theory and all of the QCD inspired models have predicted its existence of glueball without any doubts.

We also claim in this paper that according to strong interaction theory QCD, the Odderon consisting of three reggeized gluons must play a significant role in describing hadron-hadron scattering. In order to prove this conclusion we study $\bar{p}p$ and pp elastic scattering at high energies. Our calculations in this work show that the Odderon contributions are really essential for fitting the experimental data of pp and $\bar{p}p$ elastic scattering at $\sqrt{s} = 52.8$ GeV. That is, the absence of the Odderon contribution could not fit the corresponding experimental data, but the inclusion of the Odderon contributions reproduce the data successfully. This fact is a strong evidence that the Odderon is of existence and then offers one more evidences that QCD is a correct theory of strong interaction.

According to our results of $\bar{p}p$ and pp scattering investigation, we strongly recommend to search for Odderon in the $\bar{p}p$ and pp elastic scattering processes at high energies and odarate momentum transfer $|t|$. We also suggest to measure differential cross sections of the other diffractive processes such as $\pi^{\pm}p$, $K^{\pm}p$, and γp, $\gamma\gamma$ processes, which are purely diffractive processes in which there are no quantum numbers exchange between the two colliding particles. In one word, we exploit the gluonic origin and glueball nature of the Reggeon and Pomerons from the fundamental theory of strong interaction, QCD. We propose to search for glueball and Odderon in high energy $\bar{p}p$ and pp and other diffractive processes where new physics and new particle may show up clearly into our vision.

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