Some Remarks on the Pomeron and the Odderon in Theory and Experiment

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Abstract

On March 19-21, 1998, a workshop devoted to questions of the pomeron and the odderon in high energy scattering was held in Heidelberg. This note gives a personal account of some of the issues discussed at this workshop. Of course, misconceptions and misunderstandings are to be blamed on us, not on the other participants of the workshop. A puzzle of odderon physics is identified and a convenient reaction for its experimental study is discussed.
The pomeron

The pomeron as an effective object whose exchange governs high energy diffractive reactions is well established phenomenologically. It carries vacuum quantum numbers, \( C = P = +1 \). A very successful theoretical description of diffractive hadron-hadron reactions in terms of Regge language [1] was developed in [2]. How to derive these pomeron effects in the framework of QCD is still a problem lacking a complete solution [3]. The basic suggestion was made more than 20 years ago in [4]: In the simplest picture the pomeron is some sort of two-gluon exchange.

With the HERA discovery of the rapid rise of the structure function at small \( x \), and the observation of “hard” diffractive reactions first at the CERN collider [5] and then at HERA [6], the situation has changed dramatically. We now talk of a “soft” pomeron, responsible for example for the slow rise with energy of hadron-hadron total cross-sections, and a “hard” pomeron, revealed first in the behaviour of the proton structure function at small \( x \). This immediately raises the question whether there are two separate pomerons [7], or whether instead the soft pomeron becomes progressively harder as \( Q^2 \) increases [8].

The controversy in the literature about this question is related to another matter of disagreement: whether the effect of single-pomeron exchange is significantly reduced by multiple exchange. Certainly, such “shadowing” must occur at some level, but the magnitude of its effect on total cross-sections cannot be calculated. The simplest assumption is that it is rather small, and then one explains the apparent hardening of the pomeron with increasing \( Q^2 \) by saying that the soft and hard pomerons are separate, with the relative size of their contributions changing with \( Q^2 \). On the other hand, it could also be that there is a single pomeron which is rather hard, but that in soft processes the shadowing is sufficient to reduce its apparent hardness [8].

As discussed above, the transition from the soft to the hard pomeron regime has been studied extensively in \( ep \) scattering. Another interesting reaction for such studies is vector meson production in two photon processes at \( e^+e^- \) colliders (Fig. 1)

\[
\gamma(q_1) + \gamma(q_2) \rightarrow V_1(p_1) + V_2(p_2)
\]

\( V_1, V_2 = \rho^0, \omega, \phi, J/\psi \ldots \) (1)

At least to some extent the initial photons will act like hadrons in the sense of the vector dominance model. In (1) we can have small or large virtualities \( |q_1^2|, |q_2^2| \) of the photons in the initial state and light or heavy vector mesons in the final state. It will be very revealing to see which combinations of the initial and final states correspond to either the soft or the hard pomeron regime. For theoretical work on this question we refer to [10]. An experimental study of the reaction (1) at least for \( V_1 = V_2 = \rho^0 \) should be feasible at LEP2 [11].

Until very recently, there was good reason to believe that, while the soft pomeron is surely nonperturbative and therefore very difficult to analyse with the theoretical techniques at present available, the properties of the hard pomeron can be calculated from perturbative QCD. In suitable hard processes we can undoubtedly have reactions where the exchange of two perturbative gluons having together \( C = P = +1 \) dominates. Simple two-gluon exchange gives a Regge trajectory \( \alpha_P(t) = 1 \). Higher order corrections to such
an exchange in perturbative QCD (pQCD) should under suitable conditions lead to effects associated with the so-called “Lipatov pomeron” [12, 3]. Up to this year these corrections were estimated to be very large, changing the intercept from 1 to $\approx 1.4$. More recent calculations, on the other hand, predict a very small, perhaps even negative, change of intercept [14]. Ways to look for effects typical of these pQCD radiative corrections connected with the Lipatov pomeron have been discussed by many authors [14].

An approach to the theory underlying the soft pomeron has been developed in [15, 16, 17, 18]. The nonperturbative QCD-based model which gives a microscopic description of the soft pomeron is indeed quite successful in comparison with experiment on hadron-hadron elastic scattering [17, 18, 19] and a number of other reactions [20]. A very similar approach to hard diffractive phenomena as observed at HERA was developed in [21]. How to relate this approach to the Regge language is still unclear, but there are interesting ideas in this direction [22].

The odderon

Now we come to the odderon, which was introduced as the $C = P = -1$ partner of the pomeron in terms of Regge language in [23]. Let us start with the perturbative regime. Undoubtedly there are reactions which are dominated in a suitable kinematic regime by the exchange of 3 perturbative gluons carrying together $C = P = -1$. An example where this is believed to be the case is large angle $pp$ scattering [24] with the dominant diagrams indicated in Fig. 2.

Clearly this perturbative odderon, the partner of the perturbative two-gluon pomeron, exists and it has been observed experimentally. As with the pomeron, the question arises of pQCD corrections to this type of odderon. A lot of theoretical work has been devoted to this [25]-[28] and the result seems to be that such corrections have a small effect changing for instance the (effective) intercept of the odderon trajectory $\alpha_0(0)$ from 1 for the “naked” 3 gluon exchange by less than 10 % [26, 28, 29]. Thus our conclusion is that – as for the pomeron case – it will be hard to establish experimentally for this type of odderon the particular pQCD effects connected with the higher-orders summation in the spirit of Lipatov.

It is our opinion that effects of $C = P = -1$ exchange in soft high-energy hadronic reactions will again involve the nonperturbative features of QCD in an essential way [16, 18]. This type of odderon is the one introduced originally in terms of Regge language and gives rise for instance to a difference between the amplitudes of $pp$ and $p\bar{p}$ elastic scattering at $t = 0$. Such a difference has indeed been seen [30] in the dip region in high-energy $pp$ and $p\bar{p}$ elastic scattering, but at $t = 0$ data on $p\bar{p}$ for $\sqrt{s} \approx 0.5$ TeV [31], together with dispersion relations instead of the as-yet unavailable $pp$ data at similar energies, are usually interpreted as giving tight bounds for such a difference:

$$|\rho_{pp}(s) - \rho_{p\bar{p}}(s)| \lesssim 0.05,$$  \hspace{1cm} (2)

where

$$\rho(s) = \frac{\text{Re} \mathcal{T}(s, t)}{\text{Im} \mathcal{T}(s, t)}\bigg|_{t=0}. \hspace{1cm} (3)$$
For a different view see [32].

For us, the puzzle of odderon physics is: why has the soft odderon not been observed so far at $t = 0$? Various suggestions to explain this fact have been made [26, 27, 33, 34]. In [35] it was argued that in the framework of the model for high energy diffractive reactions of [16, 17] the odderon should not couple in elastic meson-meson, meson-baryon and meson-antibaryon scattering

\[
M + M \rightarrow M + M \\
M + B \rightarrow M + B \\
M + \bar{B} \rightarrow M + \bar{B}
\]

and also not in baryon-baryon and baryon-antibaryon scattering

\[
B + B \rightarrow B + B \\
B + \bar{B} \rightarrow B + \bar{B}
\]

if the baryons have a spatial linear structure, consisting of a quark and a diquark. For baryons where the three valence quarks are well separated in star-like configurations, large odderon effects are predicted. Thus, in this model the soft odderon effects are related to the internal baryon structure. Large effects from the soft odderon are predicted for inelastic diffractive processes, for example double diffractive break-up,

\[
B_1 + B_2 \rightarrow B_1^* + B_2^*
\]

where $B_1^*$ and $B_2^*$ stand for diffractively excited baryons and for continuum states (Fig. 3).

A particularly convenient reaction where all aspects of odderon physics could be studied seems to be exclusive $C = +1$ meson production in $ep$ collisions [36, 37], both without and with diffractive proton breakup:

\[
e + p \rightarrow e + M + p, \\
e + p \rightarrow e + M + N^*.
\]

Here both $\gamma O$ and $\gamma \gamma$ exchange can contribute (Fig. 4). For $Q^2 = -q^2 \lesssim 0.5 \text{ GeV}^2$ and light mesons $M = \pi^0, \eta, \eta', f(1270)$, we expect to have “soft” odderon exchange. The prediction of [33, 38] is that, if the proton has a quark-diquark structure, the amplitude should be small for the elastic case, i.e. for $p$ in the final state. On the other hand, a large amplitude is predicted for diffractive breakup, for instance for $N(1535)$ (a state with $J^P = 1/2^-$) production. If we go now to heavier mesons, $M = \eta_c, \eta_b$, and/or increase $Q^2$ beyond $1 \text{ GeV}^2$, we should come into the perturbative regime where the reactions (7) should be dominated by the exchange of three perturbative gluons [39]. An additional bonus for the reactions (7) is that the interference of the $\gamma O$ with the $\gamma \gamma$ exchange amplitude allows one to get information on the phase of the odderon exchange amplitude. Thus, our conclusion is that it should be very worthwhile to study the reactions (7) experimentally and this can indeed be done at HERA [40].
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Figure Captions

Fig. 1: Vector meson production in two photon processes at $e^+e^-$ colliders

Fig. 2: Three gluon exchange in large angle $pp$ scattering

Fig. 3: Double diffractive breakup in baryon-baryon collisions with odderon exchange

Fig. 4: $C = +1$ meson production in $ep$ collisions with elastic or inelastic proton scattering
Fig. 1
Fig. 2

Fig. 3
Fig. 4