

THE ODDERON: THEORETICAL STATUS AND EXPERIMENTAL TESTS

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I review the theoretical and experimental status of the Odderon with emphasis on recent developments.

1 Introduction

The Pomeron has a close but less well known relative: the Odderon. While the Pomeron is a very interactive chap the Odderon has a rather shy personality. That might be a consequence of its negative C -parity, but is possibly also due to its difficult youth. After it was born¹ in 1973 and obtained its name two years later² the Odderon experienced a hard time in which many of the experts even denied it the right to exist. In other words: there was a widely accepted but wrong belief that an exchange with negative C -parity quantum number persisting even at high energies in hadronic collisions could not exist. By now the Odderon has become a well-established concept, and it is widely appreciated that the Odderon can tell us many interesting things about high energy scattering in QCD. That is: if we get hold of it – which turns out to be a surprisingly difficult task.

This year marks the 20th anniversary of the ‘Blois Workshops on Diffractive and Elastic Scattering’ as well as the 30th anniversary of the baptism of the Odderon. It is therefore a pleasure for me to review the status of the Odderon at this conference in the beautiful surroundings of the Château de Blois. The Odderon always attracted considerable interest at the Blois workshops, and the proceedings of these conferences offer rich material about various aspects of the Odderon and about its ups and downs, see especially the talks by Basarab Nicolescu^{3,4}. In the present contribution I will mainly concentrate on recent developments. Ref.⁵ contains a more comprehensive review of the Odderon.

2 Basics and Experimental Status

The Pomeron carries vacuum quantum numbers and hence is even under charge conjugation. The Odderon is also a color singlet exchange but has negative C -parity and can therefore lead to differences between particle-particle and particle-antiparticle scattering if it is not strongly suppressed at high energies, that is if its intercept is not far below one. In QCD the Odderon can be formed by three gluons in a symmetric color state.

The nonperturbative Pomeron is a complicated but certainly a predominantly gluonic object since quark exchanges are in general suppressed at high energies. In the simplest picture it can be understood as a two-gluon exchange in the t -channel. The experimentally observed growth of all hadronic cross sections with energy provides clear evidence for the Pomeron. Since two-gluon exchange can be observed in all hadronic interactions and is so important one should expect that three-gluon exchange is at least not completely absent. Obviously, one would expect a suppression by a power of the coupling α_s for the additional gluon, but for low momenta α_s is in fact not too small. According to this reasoning there should be a good chance to see (nonperturbative) Odderon exchange in a large number of processes. Surprisingly, the contrary is true: experimentally the Odderon is extremely difficult to find. So far we do not yet have a good explanation for this striking result. If we do not find one this might cast considerable doubt on our general understanding of high energy scattering in terms of gluon exchanges.

The best but still weak experimental evidence for the Odderon was found as a difference between the differential cross sections for elastic pp and $p\bar{p}$ scattering at $\sqrt{s} = 53 \text{ GeV}$ at the CERN ISR.⁶ While the pp cross section has a characteristic dip at around $t = -1.3 \text{ GeV}^2$, the $p\bar{p}$ cross section only levels off at that momentum transfer. This difference is typical for a $C = -1$ exchange and cannot be explained by mesonic reggeons only. Instead, Regge type models with an Odderon as a simple pole⁷ give a good description of the data, an even somewhat better description is obtained with a different Odderon singularity motivated by the (functional) maximality of hadronic cross sections.⁸ However, simultaneous data for both pp and $p\bar{p}$ are only available for one energy, and are unfortunately not very precise. It seems difficult to describe those data without an Odderon contribution, but the theoretical description requires to invoke Regge fits with a large number of parameters. An important observation is that the Odderon exchange is – in contrast to the Pomeron – particularly sensitive to the internal structure of the colliding hadrons.⁹ Interestingly, both Regge type fits^{7,8} find that the Odderon dominates the region $|t| > 3 \text{ GeV}^2$ both for pp and for $p\bar{p}$ elastic scattering. Unfortunately, the data in this region are only available for a rather small range of energies. Future measurements at other energies might offer a chance to study the energy dependence of that region and – possibly – to identify the Odderon. In the future also a measurement of the spin dependence of elastic pp scattering at small $|t|$ will offer a good chance to find the Odderon.¹⁰

Another interesting observable related to Odderon exchange is the difference of the ρ -parameters for pp and $p\bar{p}$ scattering, where the ρ -parameter is defined as the ratio of the real and imaginary parts of the forward scattering amplitude. Unfortunately, the extraction of the ρ -parameter from the experimental data is rather difficult, and as a consequence the situation regarding the Odderon is not conclusive. For a more detailed account we refer to Ref.⁵.

In the observables mentioned so far the Odderon contribution is only one of several exchanges in the scattering process and therefore difficult to extract. Recently, more attention has been given to exclusive processes in which the Odderon is (besides the well-understood photon) the only possible exchange. Already the observation of these processes would therefore establish the existence of the Odderon, independently of any model assumptions. An important process of this kind is the diffractive production of pseudoscalar and tensor mesons in ep scattering.^{11,12} While heavy mesons can be produced only at very low rates (see Ref.⁵) sizable cross sections have been estimated for the photoproduction of pions and for f_2 and a_2 mesons^{13,14} based on model assumptions for nonperturbative QCD that work well in Pomeron exchange processes. So far, however, no signal has been observed experimentally. The data for pion production lie far below the estimate¹⁵ which can probably be attributed to chiral symmetry effects which had not been properly taken into account.¹⁶ For the tensor mesons only preliminary data are available¹⁷ which are below but not far from the theoretical estimates. Effects that could lower the theoretical expectations for the tensor mesons (and for the pion) are an unexpectedly low Odderon intercept, the suppression of the Odderon-proton coupling due to the internal structure

of the proton, as well as the possibility that the assumptions of the nonperturbative model are not adequate to three-gluon correlations relevant for the Odderon.¹⁶ Hence, although the data do not show an Odderon at the originally expected rate they also do not completely exclude it.

A promising possibility is to look for interference effects¹⁸ between Pomeron and Odderon exchange which is possible in diffractively produced final states which are not eigenstates under C -parity. Charge-asymmetries for example should be sizable (up to 15 %) both in electro-¹⁹ and photoproduction²⁰ of pion pairs in ep scattering. Other exclusive processes that offer chances to find the Odderon are double diffractive vector meson production in hadron-hadron collisions²¹, the quasidiffractive process $\gamma\gamma \rightarrow \eta_c\eta_c$ at a future linear collider^{22,23}, and possibly even the diffractive production of exotic hybrid mesons in ep scattering.²⁴

3 Recent Theoretical Developments

In perturbative QCD the Odderon is described by the BKP equation^{25,26} which generalizes the BFKL equation^{27,28} for the Pomeron to three interacting gluons in the t -channel. The BKP equation exhibits interesting mathematical properties like conformal invariance in impact parameter space and holomorphic separability²⁹. Furthermore it is equivalent to an integrable system³⁰, namely the XXX Heisenberg chain of $SL(2, \mathbf{C})$ spin zero.^{31,32}

Two explicit solutions of the BKP equation have been found: the JW solution³³ has an intercept of 0.96 while the BLV solution³⁴ has an intercept of exactly one which means that its energy dependence is at most logarithmic. The wave functions corresponding to the two solutions have characteristically different behaviour. While the JW solution vanishes when two of the three gluons are at the same point in transverse space, the BLV solution is a superposition of wave functions in each of which two gluons are always at the same point in transverse space. According to this qualitative difference of the wave functions the two solutions have very different couplings to external particles. Here the reggeization of gluons in high energy scattering is crucial, which in a nutshell amounts to the fact that whenever two gluons are at the same point in transverse space they behave like a single gluon. This happens in the BLV solution which is indeed a superposition of two-gluon Pomeron eigenfunctions (with odd conformal spin to account for the negative C -parity). In general, one finds³⁵ that the most general state of n gluons in the t -channel can (in leading order) couple only to external particles with at least n constituents. If less constituents are available only reggeizing solutions will be projected out of the general wave function. Therefore the JW solution can couple only to external particles with three constituent, for example baryons, but not in leading order to quark-antiquark pairs (color dipoles). The BLV solution on the other hand can couple to all hadronic particles since they always have at least two constituents. The different coupling of the two solutions to external particles is phenomenologically much more important than the difference between their intercepts which for all practical purposes can be considered equal.

There are different approaches to high energy scattering in perturbative QCD. For a long time the Odderon had been studied only in the traditional approach based on the resummation of large logarithms of the energy which in the case of the Odderon gives rise to the BKP equation. With increasing energy it becomes important to take into account also exchanges with more gluons in the t -channel. In the resummation approach this eventually leads to the extended generalized leading logarithmic approximation (EGLLA, see Ref.³⁶) in which the number of gluons is allowed to fluctuate in the t -channel. If one considers up to six gluons one can obtain a vertex describing the splitting of a Pomeron into two Odderons^{36,37} from a general two-to-six gluon vertex. The EGLLA has now also been applied to the Odderon channel³⁵ and first steps towards the calculation of the effective three-to-five gluon vertex of the EGLLA have been made.

Recently, the Odderon has also been found in other approaches to high energy QCD. In the dipole picture the Odderon was found in Ref.³⁸. In agreement with the argument given above

only the BLV solution can be obtained in that approach. In the color glass condensate approach the Odderon has been discussed in the context of classical fields³⁹, and also its quantum evolution has been considered in detail.⁴⁰ Here both solutions, JW and BLV, can be found when suitable external sources are considered. Both the color glass condensate approach and the dipole picture are particularly well suited for studying the effects of parton saturation inside highly energetic hadrons. Interestingly, it turns out that the Odderon is suppressed due to saturation if one takes into account the effects of Pomeron-Odderon interactions in first approximation.^{38,40} Further detailed studies will tell us to what extent this effect can explain the apparent smallness of Odderon exchange in many reactions that we have described in the previous section. Possible phenomenological consequences of Pomeron-Odderon interactions have also been discussed in the context of antishadowing in neutrino-nucleus collisions.⁴¹

From a theoretical point of view only very little is known about the Odderon in soft and hence nonperturbative reactions. An interesting proposal⁴² is to infer the intercept of the soft Odderon from its Regge trajectory. So far only the masses of the lightest two glueballs which can lie on that trajectory, the 1^{--} and 3^{--} , are known and indicate a very low and even negative Odderon intercept if a linear trajectory is assumed.⁴³ But it is also possible that the 1^{--} glueball actually lies on a daughter trajectory and then the Odderon intercept could be considerably higher and indeed close to one. Therefore there is a great interest in a future lattice calculation of a 5^{--} glueball which would help to clarify the situation of the soft Odderon.

4 Summary and Outlook

According to our understanding of high energy scattering based on the picture of gluon exchanges the existence of the Odderon is very likely. Surprisingly though, the experimental evidence for it is rather weak. Especially exclusive reactions that can be caused only by the Odderon offer good chances to finally establish its existence. In perturbative QCD the Odderon is under rather good control. It is already by itself a very interesting object from a theoretical point of view. It further is an important ingredient in effective theories of high energy scattering that are currently discussed. New insight into the behaviour of the nonperturbative Odderon can be expected from lattice studies of glueball trajectories.

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