Double Pomeron Exchange: the early years

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Abstract. I review the early experimental searches for double pomeron exchange, the first observations at the CERN Intersecting Storage Rings (ISR) and further studies at the SPS and Tevatron (fixed target). I only have space for a superficial coverage of some highlights, and will not cover later colliders with $\sqrt{s} > 100$ GeV.

INTRODUCTION

In the late 1960's, before the introduction of QCD (Gross, Politzer and Wilczek showed that SU(3) is asymptotically free in 1973) hadronic interactions were mainly described in terms of Regge trajectories. Regge theory was based on complex scattering amplitudes $A(s,t)$ for reactions such as $1 + 2 \rightarrow 3 + 4$, with s = (centre-of-mass energy)^2 and t = (four-momentum transfer)^2 from particles $1 \rightarrow 3$, and was built on the principles of analyticity, unitarity and crossing symmetry. Although 4-momentum is transferred between the colliding particles, it is *not* carried by a particle (except for a virtual photon, γ, in Coulomb interactions) and is not emitted from one and absorbed by the other (that would be frame-dependent, reversible by a boost). In the centre-of-momentum frame of an elastic collision no energy is transferred, only 3-momentum; it is spacelike. The invariant 4-momentum exchange is carried by a sum of virtual states with the same quantum numbers, lying on a "Regge trajectory" with complex angular momentum $\alpha(t)$, approximately linear in t, which determines the behaviour of $A(s,t)$. The optical theorem relates the total cross section to the imaginary part of the $t = 0$ scattering amplitude. This leads to a simple expression for the total pp cross section, $\sigma_{tot} = \mathbb{R} \; s^{\alpha_{\mathbb{R}}(0)-1} + \mathbb{P} \; s^{\alpha_{\mathbb{P}}(0)-1} \approx \mathbb{R} \; s^{-0.4525} + \mathbb{P} \; s^{0.0808}$ [1]. Two terms are needed because the total and elastic pp cross sections fall with energy, flatten and then rise. The minimum, above which the $\mathbb{P}$ term becomes dominant, happens at $\sqrt{s} \sim 20$ GeV. The discovery that the total pp cross section rises at the CERN ISR was the first clear evidence for the existence of the pomeron. It has the same quantum numbers as the vacuum. The Reggeon trajectory $\alpha_{\mathbb{R}}(t)$ is best measured with charge exchange reactions, such as $\pi^- + p \rightarrow \pi^0 + n$ (which cannot yet be calculated in QCD) and when continued to positive $t \equiv M^2$ passes through integer values of $\alpha(M^2) \equiv J$ at the squared-masses of known resonances (ρ, a_2, etc.). The pomeron trajectory, which has intercept $\alpha_{\mathbb{P}}(t = 0) \sim 1.08$ (see above), with a slope $\alpha' \sim 0.2$ GeV^{-2} extrapolates to the next integer, $J = 2$, at $M^2 \sim 4$ GeV^2 i.e. $M \sim 2$ GeV, and should correspond to a tensor ($J = 2$) glueball state. The lightest glueball is expected to be a scalar ($J = 0$) and cannot be on the pomeron trajectory; its mass from lattice QCD calculations is expected to be ~ 1600 MeV. Now, in 2014, the glueball sector is still unclear, but both $f_0(1500)$ [2] and $f_0(1710)$ [3] are considered good candidates for a scalar glueball. Double pomeron exchange, DIPE, selects isoscalar states with even spin, positive parity and C-parity, and together with the glue-dominated nature of the pomeron, it provides an excellent channel for $J = 0, 2$ glueball searches [4]. Glue-dominated states with *any* quantum numbers can also be pair-produced in DIPE.

Experimental searches for DIPE started already in 1969 [5] in the Brookhaven 80" bubble chamber with 25 GeV/c pions: $\pi^- p \rightarrow \pi^- + (\pi^+ \pi^-) + p$. The centre-of-mass energy was very low, $\sqrt{s} = 6.9$ GeV, and they found 250 events with the characteristics of multi-Regge exchange but not DIPE; ρ- and ω-Reggeon exchanges dominated. Later bubble chamber searches [6], even with beams up to 205 GeV/c, did not succeed in making an observation of DIPE. The story is given in some more detail in Ref. [7]. Upper limits on the cross sections were $\sigma_{DPE} < 44 \; \mu$b; while a 20 μb limit came from Ref. [8] using a 69 GeV/c proton beam on a liquid hydrogen target with electronic detectors.

The CERN Intersecting Storage Rings, ISR, started in 1971 producing pp collisions at much higher energies than any fixed target experiments (even today, being equivalent to 2.1 TeV/c protons on a hydrogen target). In 1972 the Small Angle Spectrometer at the CERN ISR, at $\sqrt{s} = 45$ GeV observed a peak at the Feynman variable $x_F = p_z/p_{beam} \gtrsim 0.95$ corresponding to high mass diffractive dissociation [9]. From kinematics, a proton with $x_F > 0.95$ is adjacent to a rapidity gap $\Delta y > \ln(1/(1 - x_F)) = 3$. A good "rule-of-thumb" for pomeron-dominance in an
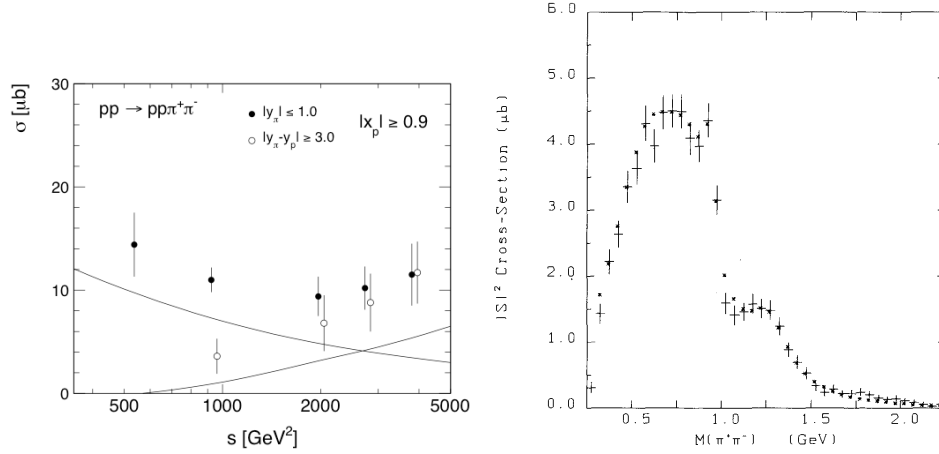
FIGURE 1. *(left)* Experimental results on σ_{DPE} up to ISR energies, with Regge fits. *(right)* The central exclusive $\pi^+\pi^-$ S-wave cross section distribution at $\sqrt{s} = 63$ GeV (SFM).

inelastic interaction is to have a proton with $x_F > 0.95$ *or* a rapidity gap $\Delta y > 3$. The ISR data were fit to a triple-Regge model with a Reggeon, $I\!R$ or $I\!P$, coupled to the proton and interacting with the other proton with another Reggeon/pomeron exchange. A key theoretical issue was whether the triple-pomeron coupling $g_{I\!P I\!P I\!P}$ vanishes at $t = 0$; the data showed otherwise. The phenomenology, with fits to the data, implied that one should have $I\!P + I\!P \rightarrow X$ reactions, i.e. DIPE, and revived interest in the process.

The first observation of DIPE came in 1976 [10] by experiment R407/408 at the Split Field Magnet (SFM) facility at the ISR. The SFM facility had a dipole field in the forward directions, but in the central region the field was complicated (with zero field at polar angle $\theta = 90°$, i.e. $\eta = 0$). Clearly the study of DIPE *with little background* required colliding beams, ISR and above, and triggerable electronic detectors. This was reinforced by the last published hydrogen bubble chamber study [11] at Fermilab, with 147 GeV/c π, K, and p beams, finding only 47 candidate events in 500,000 pictures, and quoting $\sigma \sim 20$ - 50 μb. In the post-ISR years many excellent studies of central exclusive hadron production on a fixed target were done with $\sqrt{s} = 13$ - 29 GeV using the Omega-spectrometer, with many different central states [12]. But some $I\!R + I\!P$ backgrounds were always present. The last fixed target DIPE experiment was E690 [13] at the Fermilab Tevatron with an 800 GeV/c proton beam ($\sqrt{s} = 40$ GeV). Exclusive $X = \pi^+\pi^-, K_s^0 K_s^0, K_s^0 K^{\pm}\pi^{\mp}$ and $\phi\phi$ channels were studied. The slow recoil proton was not measured, but was inferred from the missing mass squared of the event ($M_{miss}^2 \sim m_p^2$). A partial wave analysis (PWA) was made to select S-wave ($J = 0$) and D-wave ($J = 2$) intensities. The S-wave $\pi^+\pi^-$ spectrum shape up to 2000 MeV is essentially identical to that measured earlier at the ISR, with only a small D-wave $f_2(1270)$. However, if the fast proton has $p_T > 1$ GeV/c the $f_2(1270)$ becomes more prominent. Much later data from CDF [14] showed a stronger $f_2(1270)$ signal, not detecting the leading protons but allowing dissociation. It seems that the DIPE spectra are different when the protons are detected at small $|t|$ and when only gaps are required; this could now be tested directly in CMS-TOTEM low-pileup runs at the LHC, by comparing central states with leading protons and with leading showers in the Forward Shower Counters, FSC.

Fig.1(left) shows CEP cross sections vs. s, fit to a falling $I\!R$ component and a rising $I\!P$ component, which dominates (in this kinematic region) only for $\sqrt{s} \gtrsim 50$ GeV. If one instead selects $|x_p| > 0.95$ the non-DIPE component is reduced and the DIPE signal emerges earlier.

Some ten years after the first observation of DIPE, more detailed studies from both the SFM and the Axial Field Spectrometer, AFS, were published. Breakstone *et al.* [15, 16] at $\sqrt{s} = 45$ - 63 GeV at the SFM selected 4-track events with two leading particles, assumed to be protons, separated by rapidity gaps $\Delta y > 3.0$ from a pair of pions each with $y_\pi < 1.0$. A 4-C fit to $p + \pi^+\pi^- + p$ with $x_F(p) > 0.9$ cleaned up the sample. They found t_1 and t_2 to be uncorrelated, and to have an exponential slope $b = -6.1$ GeV^{-2}, half the elastic slope, for both t_1, t_2, and $(t_1 + t_2)$, as expected for DIPE. The cross section is about 10 μb, showing some rise through this energy range [17]. The $M(\pi\pi)$ spectrum rises from threshold up to 1000 MeV, with no sign of a ρ-meson (forbidden in DIPE), and then drops rapidly, see Fig.1(right). This behavior is called a "cusp", occuring when the $K\bar{K}$ threshold opens, but the narrow $f_0(980)$ meson occurs at the same mass. A bump in the cross section looks like the $f_0(1270)$ state, but a partial wave analysis showed

that the $J = 2$ D-wave is dominated there by S-wave, see Fig.1(right). This raises the question whether the data all the way up to 1500 MeV, where there is a break, are dominated by the $f_0(500)/\sigma$, a very broad (Γ = (400 - 700) MeV) $I^G J^{PC} = 0^+ 0^{++}$ (poorly understood) state, destructively interfering with the $f_0(980)$ to form a dip.

The AFS was designed for high-E_T physics, with a uranium-scintillator calorimeter covering $\Delta\phi = 2\pi$, and co-discovered high-E_T jets with UA2 at the S$p\bar{p}$S collider. To search for glueballs in DIPE, sets of drift chambers for proton tracking were added [18, 19] along the beam pipes, with veto counters covering $1.5 < |\eta| < 3$. Events kinematically compatible with $p + h^+ h^- + p$ with $x_p > 0.95$ were selected, and the central hadrons were identified by ionisation, $\frac{dE}{dx}$. At $\sqrt{s}$ = 63 GeV there were 87,000 $\pi^+\pi^-$, 523 K^+K^-, and 64 $p\bar{p}$ events, with a small amount of data at $\sqrt{s}$ = 45 GeV. The general features are similar to those in Fig.1(right), including S-wave dominance up to about 1500 MeV, apart from a small $f_0(1270)$. The only established [20] scalar meson in this region is the broad $f_0(1300)$. With higher statistics, the data extend to 3500 MeV, showing a broad bump from 1500 to 2500 MeV.

The ISR also provided $\alpha - \alpha$ collisions at $\sqrt{s}$ = 126 GeV, and both the AFS and the CERN-Naples-Pisa-Stony Brook experiment [21] measured $\alpha + \pi^+\pi^- + \alpha$ events, clearly coherent as the α stay intact while pions are created. The mass spectrum has the same shape as in pp, within the large statistical uncertainty, the t-slope is about half that of elastic $\alpha\alpha$ scattering, and σ(DIPE) is about a factor $2\times$ higher.

The SPS fixed target studies with the Ω-spectrometer provided a wealth of information, but at too low $\sqrt{s}$ for DIPE dominance. Our goal should be to get much higher statistics (e.g. 10^6 events/channel) with both protons measured at high $\sqrt{s}$, e.g. at RHIC or the LHC, and in many channels with identified hadrons including (but not only) K^+K^-, $K^0_S K^0_S$, $\phi\phi$, $\eta\eta$, $\pi\pi KK$. This could actually be done in about a week of low pileup running at the LHC. If there is, as expected in QCD, a scalar glueball with mass > 1000 MeV it will probably be quite wide and therefore have such a short lifetime that if produced inclusively it will decay within the hadron size ~ 1 fm. It will not be an isolated hadron, but live and die in a "messy" environment. Only in direct DIPE production will it be alone, in a clean (in fact, vacuum) environment. This is diffractive excitation of virtual strongly interacting states in the vacuum! Interesting!

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