Hadron Spectroscopy in Double Pomeron Exchange Experiments

Michael G. Albrow

Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Abstract. Central exclusive production in hadron-hadron collisions at high energies, for example $p + p \rightarrow p + X + p$, where the $+$ represents a large rapidity gap, is a valuable process for spectroscopy of mesonic states $X$. At collider energies the gaps can be large enough to be dominated by pomeron exchange, and then the quantum numbers of the state $X$ are restricted. Isoscalar $J^{PC} = 0^{++}$ and $2^{++}$ mesons are selected, and our understanding of these spectra is incomplete. In particular, soft pomeron exchanges favor gluon-dominated states such as glueballs, which are expected in QCD but not yet well established. I will review some published data.

Keywords: pomeron, diffraction, Central exclusive production

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INTRODUCTION

While Quantum ChromoDynamics, QCD, is usually called, and generally believed to be, THE theory of strong interactions, it has only been tested with precision (a) at distances much less than the size of hadrons, 1 fm, corresponding to high momentum transfers $Q^2 \gg 1$ GeV$^2$ where perturbation theory applies, or (b) approximating continuous space-time as a discrete lattice, as in Lattice QCD. There are many other approaches to modeling hadrons and associated phenomena at large distances, such as bag models, and string models. Regge theory is based on the sound ideas that scattering amplitudes should obey analyticity, unitarity and crossing symmetry, together with the $t$-channel exchange of continuous, complex angular momentum. Without a demonstration that QCD underlies these large distance phenomena, including confinement of quarks and gluons, we cannot claim that QCD is a complete theory of the strong interaction. Indeed potentially new and unexpected phenomena may be revealed, either experimentally or through a theoretical breakthrough. Especially interesting is the QCD vacuum. It is no exaggeration to say: “If we understood the vacuum, we would understand all of fundamental physics”. While this obviously applies to the Higgs sector at the smallest spacetime scales accessible at the LHC, it should also apply to the $\gtrsim 1$ fm scale. Any isoscalar-scalar states with $I^G J^{PC} = 0^0 +$ will be present in the vacuum as fluctuations through Heisenberg’s Uncertainty Relation $\Delta E \Delta t \gtrsim \hbar$ (as will $e^+e^-$-loops and everything else allowed). Such virtual isoscalar states can be “promoted” to a real state in a high energy collision of two hadrons (e.g. $pp$ or $p\bar{p}$). We can call this “diffractive excitation of the vacuum”, or double pomeron exchange, DIFE. (For unfamiliar readers, we can simply define the pomeron as the carrier of the 4-momentum exchanged between two protons scattering elastically at very high energy e.g. at the LHC (apart from photon exchange, which dominates at very small scattering angles). An example of double pomeron exchange is the reaction $p + p \rightarrow p + X + p$ where the protons are almost elastically scattered, carrying an outgoing momentum fraction $x_F \gtrsim 0.95$, and the central state $X$ is isolated by rapidity gaps, with no hadrons, $\Delta y \gtrsim 3$ ($\Delta y \gtrsim 4$ or 5 would be better!). The scattered (anti)proton may diffractively dissociate into a low-mass state ($p^*$) provided the longitudinal momentum of $p^*$ has $x_F \gtrsim 0.95$.

SCALAR MESONS AND GLUEBALLS

I quote from the 2010 Particle Data Group[1] Note on Scalar Mesons: “The scalar mesons are especially important to understand because they have the same quantum numbers as the vacuum ($J^{PC} = 0^{++}$). Therefore they can condense into the vacuum and break a symmetry such as a global chiral $U(N_f) \times U(N_f)$. The details of how this symmetry breaking is implemented in Nature is one of the most profound problems in particle physics.” But the identification of the scalar mesons is “a long-standing puzzle”.

Bag models and strings

Bag Models[5, 6] treat hadrons as bound states of quarks and gluons confined in a fm-size bag with a pressure and surface tension. Outside the bag is the “true vacuum”, while inside is the “perturbative vacuum”; a different phase in which quarks and gluons are free. There are several forms, the MIT bag model, the SLAC bag model, the soliton bag model, etc. Jaffe and Johnson[7] discussed hadrons with unconventional quantum numbers in the bag model, and claimed that the known \( J^{PC} = 0^{++} \) mesons in the mass range 600 - 1600 MeV/c\(^2\) may be members of a nonet of \( q\bar{q}q\bar{q} \) rather than P-wave \( qq \) states. In 1983 Jezabek and Szwed[8] argued that for glueballs the bag surface fields should be “TE” (transverse electric, in QCD) which suggests that the bags have a toroidal topology (one cannot have a transverse field everywhere on the surface of a sphere without sources). Interestingly (but I do not know whether the connection is more than coincidence) in the string models of hadrons glueballs are closed loops of string, i.e. toroids. In string models quarks and antiquarks are the open ends of directed strings, with the form of an “I” for a meson and a “Y” for a baryon or antibaryon. As glueballs are strings without ends, they have the form of an “O”. Their decay occurs by the string-loop breaking to generating new ends (\( q\bar{q} \)) as an excited meson “I”, which in turn breaks to a pair of mesons. The Regge trajectory \( \alpha(t) \) for such \( q\bar{q} \) mesons has a slope \( \alpha' \) of order 1 GeV\(^{-2}\) linking excited mesons with the same quantum numbers apart from spin. It is not unnatural for a closed loop of string to have a trajectory with smaller slope, such as that of the pomeron, e.g.[9] \( \alpha(t) = 1.081 + 0.25 \text{ GeV}^{-2}t \). A spin \( J = 2 \) state would lie on this trajectory (if it is linear) at \( M_G(2^{++}) \sim 2000 \text{ MeV/c}^2 \); that would be the tensor glueball. The scalar glueball cannot lie on the pomeron trajectory. In this model a barred loop like \( \theta \) would be allowed as a topologically different glueball. Having two-three-string junctions this would decay to a baryon-antibaryon pair (assuming it is not too light, in which case it could be stable). Barnes, Close and Monaghan[10] calculated order-\( \alpha_S \) hyperfine splitting in the spherical cavity approximation to the MIT bag. They concluded that the \( 0^{++} \) and \( 2^{++} \) glueball states could be identified with the \( t(1440) \) and \( \theta(1640) \) states, implying that the lightest scalar \( 0^{++} \) is around 1000 MeV/c\(^2\). This “may mix with the \( S'(980)^+ \)” (now \( f_0(980) \)).

Lattice QCD

In 1997 Morningstar and Peardon[11] calculated the masses of pure glueballs (in pure SU(3) gauge theory) in lattice QCD, in which space and time are treated as discrete. If the lattice spacing is much smaller than the size of a hadron (~ 1 fm) this approximation allows (computer-intensive) calculations of hadron masses in terms of one parameter (a scale with dimension “mass”). Usually this is done with different lattice spacings \( a_L \) and extrapolated to \( a_L = 0 \). Recent developments[12] predict the lightest glueballs to have \( M_G(0^{++}) = 1710 \text{ MeV} \) and \( M_G(2^{++}) = 2390 \text{ MeV} \), with uncertainties about 100 MeV and 125 MeV respectively. Mixing with \( qq \) states can affect these masses. Note that the PDG summary tables[13] (Table 1) have an \( f_0(1710) \) whose only established decay is to \( \eta \eta; \) we need to establish its other decays in DPE production. The nearest other DPE - allowed scalar is \( f_0(1500) \), and possibly both...
these resonances are mixtures of $q\bar{q}$ and $gg$ states \cite{14, 15}. The same lattice QCD calculations predict a whole spectrum of glueball states with $PC = +++, --, --$, as well as $M_G(3^{++}) \sim 3600$ MeV, that are not easily produced singly in DPE but can be produced in pairs. Some have masses around 4000 MeV/c², where we do not expect any $q\bar{q}$ mesons. It would clearly be useful to have predictions for the decay modes and widths of these states. Perhaps pair production in DPE, and radiative $\Upsilon$ decays, are the best windows on this spectroscopy.

Table I lists all the established $I = 0$ and $J^{PC} = 0^{++}, 2^{++}$ states in the PDG Summary tables \cite{13}. These can, in principle, be produced in DPE, which is a quantum number filter when the 4-momentum transfers $t_1$ and $t_2$ are small. (At larger $|t|$ other $J^{PC}$ are allowed, but are suppressed.) Above the rather narrow $f_1(1525)$ state, which decays mostly to $K^+K^-$ and is not a good glueball candidate, the information on the decay modes is very sparse. It is a challenge to measure all these (sometimes overlapping) states with their decay modes and partial wave analysis to distinguish $J = 0$ and $J = 2$. Favorited states for the lightest glueball, albeit mixed with $q\bar{q}$ states, are the scalar $f_0(1500)$ \cite{14} and $f_0(1710)$ \cite{15}.

## DOUBLE POMERON EXCHANGE: HISTORY

Low and Nussinov proposed in 1975 \cite{16, 17} that to lowest order the pomeron is a pair of gluons in a color singlet. This is still considered a very good approximation, and means that double pomeron exchange would be a good reaction to produce glueballs. Experimental searches for DPE started already in 1969 \cite{18} 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, so it was kinematically impossible to have two large rapidity gaps. They found 250 events with the two pions between the protons (in rapidity), but they had the characteristics of multi-Regge exchange, not DPE; $p^-\cdot$ and $\omega$-Reggeon exchanges dominated. Later bubble chamber searches \cite{19}, with higher energy beams (205 GeV/c), also did not succeed in making an observation of DPE. In 50,000 pictures 191 $p + p \rightarrow p + (\pi^+\pi^-) + p$ events were selected, showed no evidence for DPE and gave an upper limit on the cross sections $\sigma_{DPE} < 44$ mb. In 1975 a France-Soviet Union collaboration \cite{20} used a 69 GeV/c beam on a liquid hydrogen target. The events were all compatible with single diffractive dissociation (one rapidity gap, not two), and they quoted an upper limit $\sigma(DPE) < 20$ mb.

The first observations of DPE came in 1976 at the CERN Intersecting Storage Rings (ISR), but before discussing those we should mention the last “heroic” attempt to do this physics with a hydrogen bubble chamber. In 1980 Brick et al.\cite{21} took 500,000 pictures with 147 GeV/c $\pi$, $K$, and $p$ beams, finding just 47 DPE candidates corresponding to a cross section $\sigma \sim 20 - 50$ mb. The conclusion is that the study of DPE requires the higher $\sqrt{s}$ of colliding beams, and electronic detectors, not bubble chambers. However at CERN the Omega-spectrometer, a major fixed target facility, did many studies with beams up to 450 GeV/c, $\sqrt{s} = 29$ GeV. The full rapidity span between target and beam is $\Delta y = 2 \times \ln \sqrt{s}/M_p = 6.86$, which is on the threshold of allowing two rapidity gaps of 3 units with a central low-mass state. I return to the Omega experiments, after discussing the CERN Intersecting Storage Rings, ISR.

The ISR started producing $pp$ collisions in 1971 at much higher energies than any fixed target experiments (even today, being equivalent to 2.1 TeV/c protons on a hydrogen target). The first “evidence paper” by Baksay et al.\cite{22} was from a relatively simple experiment with no magnetic field. Small-angle protons above and below the outgoing

| Name     | $M$(MeV/c²) | $\Gamma$(MeV) | $f^G_J^{PC}$ | $\pi\pi$ | $K\bar{K}$ | Other modes |
|----------|-------------|--------------|-------------|---------|----------|-------------|
| $f_0(600)$ | 400-1200    | 600-1000     | 0 $^{0+}$   | 100 -   | -        | -           |
| $f_0(980)$ | 980±10      | 40-100       | 0 $^{0+}$   | dominant | seen     | -           |
| $f_2(1270)$ | 1275.1±1.2 | 185±3        | 0 $^{2+}$   | 84.8 $^{+2.4}_{-1.2}$ | 4.6 $^{+0.4}_{-0.4}$ | 2 $^{+2}_{-2}$ $^{2+}$ |
| $f_0(1370)$ | 1200-1500   | 150-250      | 0 $^{0+}$   | seen    | $\rho\rho$  | dominant   |
| $f_0(1500)$ | 1505±6     | 109±7        | 0 $^{0+}$   | 34.9±2.3 | 8.6±1.0 | 4 $\pi$ 49.5±3.3 |
| $f_2(1525)$ | 1525±5     | 76±10        | 0 $^{2+}$   | 0.8±0.2 | 88.7±2.2 | $\eta\eta$ 10.4±2.2 |
| $f_0(1710)$ | 1720±6     | 135±8        | 0 $^{0+}$   | seen    | $\eta\eta$  | seen       |
| $f_2(1950)$ | 1944±12    | 472±18       | 0 $^{2+}$   | seen    | $\eta\eta$  | seen       |
| $f_2(2010)$ | 2011±70    | 202±70       | 0 $^{2+}$   | -       | $\phi\phi$  | seen       |
| $f_2(2300)$ | 2297±28    | 149±41       | 0 $^{2+}$   | -       | $\phi\phi$  | seen       |
| $f_2(2340)$ | 2339±55    | 319±81       | 0 $^{2+}$   | -       | -        | $\phi\phi$  seen |
| $f_0(2510)$ | 2465±50    | 255±40       | 0 $^{6+}$   | 6.0±1.0 | -        | -           |
beam pipes were tracked in proportional chambers, a cylindrical scintillator hodoscope covered the central region and two counter hits were required, and in-between veto counters established pseudorapidity ($\eta$) gaps of at least 2 units. To avoid elastic scatters the protons were “UP + UP” or “DOWN + DOWN”. Data were taken at several ISR beam energies from $15 + 15 \text{ GeV}$ to $31 + 31 \text{ GeV}$; DIPE cross sections were in the range $16 - 28 \mu \text{b}$, less than $10^{-3} \times \sigma_{inel}$.

Although the proton momenta were not measured, assuming they had the beam momentum (a good approximation) the $t$-slope is $b = -9.9 \pm 1.8 \text{ GeV}^{-2}$, compatible with half the elastic slope as expected.

The only attempt at a large solid angle detector in the early days at the ISR was the Split Field Magnet (SFM) facility. This had a dipole field in the forward directions, but in the central region the acceptance and the magnetic field were complicated. Leading protons could be well measured, a fact exploited by experiment R407/408, who also observed DIPE in 1976 [23]. Figure 1(left) shows cross sections vs. $s$, fit[24] to a falling IR component and a rising IP component, which dominates only for $\sqrt{s} \gtrsim 50 \text{ GeV}$. If one fixes the central state to have $|y(\pi\pi)| < 1$, as $\sqrt{s}$ increases the gaps get bigger and the cross section decreases. If one instead fixes two rapidity gaps $\Delta y \geq 3$, the central region expands with $\sqrt{s}$ and the cross section rises.

**FIGURE 1.** Left: Experimental results on $\sigma_{DPE}$ up to ISR energies, with Regge fits[24]. Right: The central exclusive $\pi^+\pi^-$ invariant mass distribution at $\sqrt{s} = 62 \text{ GeV}$ (SFM[25]).

After the ISR was shut down in 1984 Breakstone et al. [25, 26] published a more detailed SFM study of a 4-C fit to $p + \pi^+ \pi^- + p$ with $x_F(p) > 0.9$ (protons and pions are assumed but not identified). They found $t_1$ and $t_2$ to be uncorrelated, and to have an exponential slope $b = -6.1 \text{ GeV}^{-2}$, half the elastic slope, for both $t_1, t_2$, and $(t_1 + t_2)$, as expected for DIPE. The cross section is about $10 \mu \text{b}$, showing some rise through this energy range [27]. The $M(\pi\pi)$ spectrum rises from threshold up to $1000 \text{ MeV}$, with no sign of a $\rho$-meson (forbidden in DIPE), and then drops rapidly, see Figure 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 nearly 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. This raised the suggestion[28] that the data all the way up to $1500 \text{ MeV}$, where there is a break, may be dominated by the $f_0(500)/\sigma$, a very broad ($\Gamma = 400 - 700 \text{ MeV}$) $f^G_pP^C = 0^+0^+$ (poorly understood) state, destructively interfering with the $f_0(980)$ to form a dip.

The Axial Field Spectrometer, AFS, was designed for high-$E_T$ physics, with a uranium-scintillator calorimeter covering $\Delta \phi = 2\pi$. To search for glueballs in DIPE, sets of drift chambers for proton tracking were added [29, 30] 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 ionization, $dE/dx$. At $\sqrt{s} = 63 \text{ GeV}$ there were $87,000 \pi^+ \pi^-$, $523 \ K^+ K^-$, and $64 \ pp$ events, with a small amount of data also at $\sqrt{s} = 45 \text{ GeV}$. The general features are similar to those in Figure 1(right), including S-wave dominance up to about 1500 MeV, apart from a small $f_0(1270)$. The only established [13] scalar meson in this region is the broad $f_0(1370)$. 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 [31] measured $\alpha + \pi^+ \pi^- + \alpha$ events, clearly coherent as the $\alpha$ 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 $\sigma$(DIPE) is about a factor $2 \times$ higher.

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 at CERN, with many different central states [32]. But some $\text{IR} + \text{IP}$ backgrounds were always present. The last fixed target DIPE experiment was E690 [33] at the Fermilab Tevatron with an 800 GeV/c proton beam ($\sqrt{s} = 40$ GeV). Exclusive $X = \pi^+ \pi^- K^0_s K^0_s \pi^\pm$ and $\phi \phi$ channels were studied. The slow recoil proton was inferred from the missing-mass-squared of the event ($M^{2}_{\text{miss}} \sim m_p^2$), 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.

Very little DIPE data was taken at the CERN $SpbS$, but papers from experiments UA1[34] and UA8[35] are discussed in Ref.[37].

The Tevatron $p\bar{p}$ collider with $\sqrt{s} = 1960$ GeV was the perfect machine for DIPE; at $\sqrt{s} = 1960$ GeV we have $\gamma_{\text{beam}} = 7.64$. With a good solenoidal central detector, with charged hadron identification by time-of-flight as in CDF, one can have rapidity gaps of 5 units adjacent to the leading protons, essentially pure pomeron exchange. (Photon exchange can also give such large gaps and both $\gamma$ IP and $\gamma \gamma$ events were observed when the central state is forbidden in DIPE, as for $e^+e^-, \mu^+\mu^-$, and $J/\psi$.) Unfortunately an early installation of Roman pots to measure elastic scattering and single diffraction was not retained long enough to study DIPE with both protons detected. However sets of scintillator paddles (Beam Shower Counters, BSC) were installed around the beam pipes, and could be used as rapidity gap detectors and also for triggering. In the last months before the Tevatron shut down (September 2011) CDF recorded 10$^8$ events with two forward rapidity gaps, and two or more charged particles in the central region[36]. Of these, 127,340 events had a pair of hadrons with $Q = 0$, $p_T > 0.4$ GeV/c, and $|\eta| < 1.0$ and nothing else detected in $|\eta| < 5.9$. When the $p_T$ of the pair is large enough to have low mass acceptance, the $f_0(980)$ is seen as a small peak and sharp drop, as typical in these spectra, and it is followed by a large peak, see Figure 2, which is probably both $f_2(1270)$ and $f_0(1370)$, although unfortunately the spin states could not be separated. (The $X \rightarrow \pi^+ \pi^-$ decay is consistent with being isotropic up to 1500 MeV/c$^2$, within the limited angular coverage.)

![CDF Run II Preliminary](image)

**FIGURE 2.** The cross section for exclusive $\pi^+ \pi^-$ vs $M(\pi \pi)$ for all $p_T(\pi \pi)$, assuming the hadrons to be pions, at $\sqrt{s} = 1960$ GeV, above the rapid drop at 1 GeV/c$^2$. The data are no longer preliminary[36].

In the last two years new results on spectroscopy in DIPE have come from RHIC ($pp$-collisions at $\sqrt{s} = 200$ GeV) and CMS at the LHC. These are reported at this workshop by Sikora[38] and Khakzad[39] respectively, and I shall not discuss them here. Both experiments have a great deal more data already recorded, and we can look forward to seeing the final spectra. There are also data from CDF on channels other than the published $\pi^+ \pi^-$ that are still being

\[\text{\textit{Data, } } \sqrt{s} = 1960 \text{ GeV} \]

\[\text{\textit{Syst. uncertainties}}\]
analysed. What is really needed to make a leap forward is high statistics (e.g. $10^6$ events/channel) with both protons measured at high $\sqrt{s}$, at RHIC or the LHC, and in many channels with identified hadrons including (but not only) $K^+K^−, K^0\bar{K}^0, \phi, \eta, \eta', K^0\bar{K}^0\pi^\mp, \pi\pi\pi K$. It may be that the DIPPE spectra are different when the protons are detected at small $|t|$ than 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. This could actually be done in a few days 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 $\sim 1$ fm. It will not be an isolated hadron, but live and die in a “messy” environment. Only in direct DIPPE production (or perhaps also in $e^+e^− → \Upsilon → \gamma + X$) will it be alone, in a clean (in fact, vacuum) environment. More than 40 years after glueballs were proposed it is high time we understood the isoscalar $J^{PC} = 0^{++}$ and $2^{++}$ spectra.

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