Exclusive Hadronic Reactions at High $Q^2$*

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Abstract.

The observed scaling laws for large angle exclusive hadronic reactions are successfully accounted for by the short-distance QCD quark interchange processes. We focus on three hadronic reactions which show evidence for a slight oscillatory deviation from the expected scaling behaviour. Possible explanations for these oscillations and connections to spin observables will be mentioned. Better data from existing facilities (or a possible future KEK proton accelerator, JHP) can clarify the theoretical situation.

1 Introduction

In high energy exclusive hadronic reactions at high momentum transfers, $Q^2$, we explore the short distance $\sim 1/Q$ hadronic interactions and quark dynamics that are expected to give the dominant features of the cross sections. The measured cross sections of various exclusive hadronic reactions at large $Q^2$ have successfully confirmed the expected scaling laws of short distance QCD and the quark interchange model (QIM) discussed in, e.g. Ref.[1]. The expected power law fall-off of the differential cross sections at large angles are predicted to have the following behaviour: $\frac{d\sigma}{dt}(\theta \sim 90^\circ) \sim s^{-N}$, where $N$ depends on the specific reaction. For example, the measured $d\sigma/dt$ at $90^\circ$ for $pp$ and $\pi^- p$ elastic scattering have confirmed the power law fall-off where $N$ equals 10 and 8, respectively. In Fig.1 we show the measured $\pi^- p$ elastic scattering where the power law prediction of QIM is the obvious dominant feature for $d\sigma/dt$ versus $\ln(s)$. Note that $d\sigma/dt$ changes by ten orders of magnitude in this figure. For the two highest energies in Fig.1, $p_{lab}= 20$ and 30 GeV/c [2], the cross section at $90^\circ$ is tiny making the measurement extremely hard, and this is reflected in the large error bars at these two energies.

The data for $pp$ and $\pi^- p$ elastic scattering indicate that we have to refine QIM to account for some intriguing features of the data. The phenomenon of interest as observed in $pp$ elastic scattering is the “oscillations” with energy of $d\sigma/dt$ at $90^\circ$ about the expected smooth power

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law fall-off [1]. This puzzling behaviour has been known for some time and is seen in Fig. 2. In Fig. 2 the “scaled” cross section, $s^{10} \frac{d\sigma}{dt}$ at 90°, as a function of ln($s$) is shown. If QIM were perfect we expect a constant “scaled” cross section (within error bars). Instead we clearly see indications of “oscillations” about a horizontal line.

One question which is natural to ask is if these “oscillations” are observed in other exclusive hadronic reactions. We turn to two other exclusive reactions which possibly are even better processes to study, namely $\pi^- p$ elastic scattering and the reaction $\overline{p}p \rightarrow \pi\pi$. These two reactions are in several ways simpler theoretically than the $pp$ elastic scattering; they could show the “oscillation” phenomena more strikingly, phenomena seen but inadequately mapped out in the $pp$ case. It might even be possible to measure both the cross section $d\sigma/dt$ at high momentum transfer and the asymmetry $A_{0n}$ over the full kinematic range. Keep in mind that $A_{0n}$ is large for $\overline{p}p \rightarrow \pi\pi$ at $p_{lab} \approx 2$ GeV/c. The two reactions $\pi^- p \rightarrow \pi^- p$ and $\overline{p}p \rightarrow \pi\pi$ are simpler than $pp$ elastic scattering if only because they have fewer helicity amplitudes. A consequence of this is that there is less chance of averaging out the “oscillatory” effects partly because the QCD perturbation theory diagrams will involve fewer quark lines. An experimental consideration is
that presently the annihilation reaction $\bar{p}p \rightarrow \pi^0\pi^0$ has recently been measured and further measurements are possible at the antiproton accumulator at Fermilab.

2 The “Oscillations” about the scaling laws

The “oscillations” clearly goes beyond the $QIM$ scaling law predictions and requires some refinements of the arguments leading to the $QIM$ scaling laws. The “oscillations” of $pp$ elastic scattering, Fig.2, might also be observed in two other exclusive hadronic reactions. In Fig.3 the scaled cross section at 90° for elastic $\pi^-p$ scattering, $s^8d\sigma/dt$ is shown. This figure is taken from Blazey’s thesis [3]. In Fig.3 the $p_{lab}= 30$ GeV/c point of Fig.1 is not shown. This $p_{lab} = 30$ GeV/c point has too large errorbars to be useful. It is however clear from Fig.3 that we need more accurate data points at the higher energies, $\ln(s) > 3$ ($p_{lab} > 10$ GeV/c) to draw any firm conclusions.

At Fermilab the E760 collaboration has measured the differential cross section for the reactions $\bar{p}p \rightarrow \pi^0\pi^0$, $\bar{p}p \rightarrow \pi^0\eta$, $\bar{p}p \rightarrow \eta\eta$ and $\bar{p}p \rightarrow \pi^0\gamma$ [4]. The $d\sigma/dt$ at 90° for the $\bar{p}p \rightarrow \pi^0\pi^0$ reaction should show a power law fall-off $\sim s^{-8}$, similar to $\pi^-p$ elastic scattering. In Fig.4 the measured $d\sigma/dt$ at 90° has been multiplied by $s^8$ and plotted as a function of $\ln(s)$ [8]. The data points present evidence for some fluctuations. The highest $p$ energy at the Fermilab antiproton accumulator corresponds to the $\ln(s) \simeq 2.9$ point in Fig.4. It clearly would be desirable to have a more accurate measurement at this energy as well as at other non-measured $\ln(s)$ energies of Fig.4 before we can infer anything about a possible “oscillation” for this reaction.

The questions related to the above figures are:

\footnotesize{\begin{itemize}
  \item Data for $\bar{p}p \rightarrow \pi^+\pi^-$ can be found in Refs. [5,6,7].
\end{itemize}}
Figure 3: The cross section for elastic $\pi N \to \pi N$ scattering at $90^\circ$ scaled by a factor $s^8$ as a function of $s$. Figure from Ref. [3].

Figure 4: The “scaled” cross section $s^8 \frac{d\sigma}{dt}(90^\circ)$ for the reaction $\bar{p}p \to \pi^0\pi^0$ as a function of $\ln(s)$. Figure from Ref. [8].
1. Do we observe “oscillations” in $s^N \frac{d\sigma}{dt}(\theta = 90^\circ)$ versus $\ln(s)$ for all three hadronic reactions discussed?

2. If there are “oscillations” in all three reactions, do the “oscillations” have the same “period” in $\ln(s)$?

We clearly need more measurements to make progress in the physics understanding of these phenomena.

### 3 Spin Observables

Another useful observable relevant in the search for corrections to the $QIM$ is the analyzing power, $A_{0n}$. The reason for investigating $A_{0n}$ is the following. The two exclusive reactions $\pi^- p$ elastic scattering and $\overline{p}p \rightarrow \pi\pi$ are described by the two helicity amplitudes, $f_{++}$ and $f_{+-}$ whereas $pp$ elastic scattering requires five helicity amplitudes (only three independent ones at $90^\circ$). In short distance QCD considerations ($QIM$) helicity is conserved. A consequence of helicity conservation is that $f_{++} = 0$ for the reaction $\overline{p}p \rightarrow \pi\pi$. For $pp$ elastic scattering helicity conservation implies that the two helicity-flip amplitudes $\phi_2(++,--)$ and $\phi_5(++,+-)$ both equal zero. This means that the analyzing power $A_{0n} = 0$ for $pp$ elastic scattering and for $\overline{p}p \rightarrow \pi\pi$.

We know that the measured analyzing power

$$A_{0n} = \frac{d\sigma(\uparrow) - d\sigma(\downarrow)}{d\sigma(\uparrow) + d\sigma(\downarrow)}$$

for $pp$ elastic scattering has a significant asymmetry even at fairly high momentum transfers [9, 10]. A non-zero $A_{0n}$ in $pp$ elastic scattering implies that the $pp$ helicity amplitude $\phi_5(++,+-)$ must be non-zero and only the refinements of $QIM$ will give a $\phi_5(++,+-) \neq 0$. The same argument applies to $A_{0n}$ for the reaction $\overline{p}p \rightarrow \pi\pi$. Helicity conservation implies $f_{++} = 0$, and since

$$A_{0n} = 23m(f_{++}^* f_{+-}) / (|f_{++}|^2 + |f_{+-}|^2) \, ,$$

a measured non-zero $A_{0n}$ means we have to augment $QIM$ with helicity non-conserving processes. The $\overline{p}p \rightarrow \pi\pi$ reaction has a large asymmetry, $A_{0n} \approx +1$, for $p_{lab} \lesssim 2.2$ GeV/c ($\ln(s) \lesssim 1.8$) [11] and should be measured at higher energies. For $\overline{p}p \rightarrow \pi^0\pi^0$ a polarized gas jet target may allow measuring $A_{0n}$ even when the cross section is getting small.

Another measured spin observable shows “structure” in $pp$ elastic scattering at high $Q^2$, namely the beam target spin correlation $A_{nn}$ at $90^\circ$ up to $s = 26$ GeV$^2$ [12]. $A_{nn}$ is not predicted to be zero even if the short distance processes dominate [13, 14], but one would not
expect large variations of $A_{nn}$ in a regime where one can use perturbative QCD unless there were interference effects. For $pp$ elastic scattering at 90° there is a sum rule (independent of QCD) which says \[14\]:

$$A_{nn} + A_{ss} + A_{ll} = 1,$$

where $n$ signify a spin polarized normal to the scattering plane, and where $s$ is spin polarized perpendicular to the proton momentum in the scattering plane and $l$ is longitudinal polarized spin. This implies that even at the highest energies there are non-zero $pp$ spin observables.

4 Theoretical ideas for corrections to QIM

The observation by Brodsky and de Teramond \[15\] that for $pp$ elastic scattering we can have possible dibaryon resonances associated with the charm threshold, e.g. $pp \rightarrow \Lambda_c^+ D^0 p$ and a single resonance amplitude with $J = L = S = 1$ will give $A_{nn} = +1$. Interference with the QIM amplitude will then produce a value for $A_{nn} < 1$. They tie the “structure” of $A_{nn}$ to the opening of the $c\bar{c}$ threshold and they also show that the resonance can produce “oscillations” around the smooth power scaling fall-off for the differential cross section. We do expect resonance phenomena at the opening of new thresholds and we note that the possible “oscillations” for the two other reactions $\pi^- p$ elastic scattering and $pp \rightarrow \pi\pi$ appear at about the same energies. The task is to investigate possible $\tau\bar{c}$ threshold resonances for the two other reactions $\pi^- p$ elastic scattering and $\bar{p}p \rightarrow \pi\pi$.

Another process which could interfere with and produce some corrections to the QIM amplitudes, is the Landshoff process \[16\]. It has been proposed that this interference also could be an explanation of the $pp$ “oscillations” \[17\], \[18\], but this requires some reworking in light of recent developements \[19\]. The Landshoff process allows “independent” pairs of quarks to interact via hard gluon exchange and the different interacting quark pairs can be separated by a non-negligible impact parameter. At high $Q^2$ the longitudinal dimension and one transverse dimension will be of the order $1/Q$. The third dimension will be influenced by the size (r.m.s. radius) of the hadrons of the reaction. Naively speaking the Landshoff process suggest an energy behaviour of $d\sigma/dt(\theta = 90^\circ) \sim s^{-N_L}$ where $N_L < N$ even when QCD radiative corrections to the Landshoff process is included \[19\], \[20\]. These radiative corrections are calculated in perturbative QCD or derived heuristically. If $N_L < N$ then the Landshoff process should dominate at high energies. However, since the transverse dimensions or sizes of the hadrons have to be considered, meaning soft QCD processes are implied in the calculations, we should take the calculations of $N_L$ with a grain of salt.
The Landshoff amplitudes contain soft QCD processes where a propagator is (almost) on-shell (Sudakov form factors), called "the Landshoff pinch", see e.g. Ref. [20]. The crucial realization is that the radiative corrections give the quark-quark scattering amplitude an energy dependent phase [17]. The Landshoff process therefore allows for helicity flip in the reactions due to the “soft” transverse dimensions of the hadrons [21, 22]. This energy dependent phase acts at what one might call medium-high energy, although at asymptotic energies the phase becomes energy independent as stressed by Botts and Sterman [19, 23].

5 Conclusions

The power law predictions of QIM are highly successful. The challenge is to understand the corrections to the scaling laws. If the observed energy “oscillations” have their origin in “short” distance quark dynamics, this “oscillatory” behaviour should manifest itself in many exclusive hadronic reactions. The question being asked is if the "scaled" cross sections for both πN elastic scattering and the annihilation reaction $p\bar{p} \to$ two pseudoscalar mesons do “oscillate” with energy similar to what is observed for $pp$ elastic scattering.

A further test of the ideas presented here would be to measure $A_{0n}$ for the two reactions π $\bar{p}$ elastic scattering and $p\bar{p} \to \pi\pi$. With only two helicity amplitudes one can then expect to disentangle completely the phases and the energy dependence of both reactions and the energy “oscillations” should be evident in the amplitudes. Experimentally, since the asymmetry is very large at low energies, $p_{lab} \approx 2$ GeV/c [11], the annihilation reaction $p\bar{p} \to \pi\pi$ might be the best reaction to measure $A_{0n}$. We expect the geometric hadronic impact parameter ideas used to explain this large asymmetry for $p_{lab} \lesssim 2$ GeV/c [24] to break down at higher energies when the short distance QCD regime of exclusive hadronic reactions is reached. The onset of the perturbative QCD regime may be signaled by a significant change in the energy and angular variation of the asymmetry. For example, the very large $A_{0n}$ at 90° at $p_{lab} \approx 2$ GeV/c will become smaller and might “oscillate” with increasing energy if the QCD phenomenology outlined above is reasonable.

As stated above it is necessary to complement the measured points of Fig.4 [4] to make certain we observe “oscillations” in $s^8d\sigma/dt$ for the reaction $p\bar{p} \to \pi^0\pi^0$. The E835 collaboration at Fermilab could contribute with new measurements of this reaction. In addition, the measurement of $A_{0n}$ for $p_{lab}> 2$ GeV/c is expected to be extremely useful not only for a better understanding of the nature of the extraordinarily large asymmetry of $p\bar{p} \to \pi\pi$ observed [11], but also for monitoring the possible onset of perturbative QCD.
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References

[1] D. Sivers, S.J. Brodsky, and R. Blankenbecler, Phys. Rep. 23, 1 (1976)
[2] C. Baglin et al., Nucl. Phys. B216, 1 (1983)
[3] G. Blazey, Ph. D. Thesis, Univ. Minnesota (1987) unpublished.
[4] The E760 collaboration: T.A. Armstrong et al. Phys. Rev. D 56, 2509 (1997); J. Reid, Ph.D. thesis (1993) Penn State Univ.
[5] T. Buran et al., Nucl. Phys. B116, 51 (1976)
[6] A. Eide et al., Nucl. Phys. B60, 173 (1973)
[7] E. Eisenhandler et al., Nucl. Phys. B96, 109 (1975)
[8] G. Zioulas, LEAP94 Conf. Proc., eds. G. Kernel et al. (World Scientific, 1995) p.647; and private communication.
[9] D.G. Crabb et al., Phys. Rev. Lett. 65 (1990) 3241
[10] P.R. Cameron et al., Phys. Rev. D32 (1985)3070
[11] A.A. Carter et al., Nucl. Phys. B127, 202 (1977);
[12] E.A. Crosbie et al., Phys. Rev. D 23, 600 (1981)
[13] G. Farrar, S. Gottlieb, D. Sivers and G. Thomas, Phys. Rev. D 20, 202 (1979)
[14] S.J. Brodsky, C.E. Carlson and H. Lipkin Phys. Rev. D 20, 2278 (1979)
[15] S.J. Brodsky and G.F. deTeramond, Phys. Rev. Lett. 60 (1988) 1924
[16] P. V. Landshoff, Phys. Rev. D10 (1974) 1024; P. Cvitanovic, ibid. 10 (1974) 338
[17] B. Pire and J.P. Ralston, Phys. Lett. B117, 233 (1982); J.P. Ralston and B. Pire, Phys. Rev. Letters 49, 1605 (1982)
[18] J.P. Ralston and B. Pire, Phys. Rev. Letters 57, 2330 (1986)
[19] J. Botts and G. Sterman, Nucl. Phys. B325 (1989)62
[20] A. H. Mueller, Phys. Rep. 73, 237 (1981)
[21] J.P. Ralston and B. Pire, AIP Conf. Proc. 223, 228 (1991)
[22] C. E. Carlson, M. Chachkhunashvili and F. Myhrer, Phys. Rev. 1992, D46, 2891.
[23] J. Botts, Nucl. Phys. B353 (1990) 20
[24] S. Takeuchi, F. Myhrer and K. Kubodera, Nucl. Phys. A556, 601 (1993)