Charge exchange reaction by Reggeon exchange and $W^+W^-$-fusion

R. Schicker

Phys. Inst., University Heidelberg

Abstract. Charge exchange reactions at high energies are examined. The existing cross section data on the Reggeon induced reaction $pp \rightarrow n + \Delta^{++}$ taken at the ZGS and ISR accelerators are extrapolated to the energies of the RHIC and LHC colliders. The interest in the charge exchange reaction induced by $W^\pm$-fusion is presented, and the corresponding QCD-background is examined.

Keywords: Charge exchange reaction, Regge formalism, diffractive excitation, hadronic cross section.

PACS: 12.40Nn, 25.40Kv, 25.40Ep, 25.40Ny.

INTRODUCTION

The hadronic cross section is a fundamental quantity, its energy dependence can, however, so far not be derived by first principles from the QCD-Lagrangian. Within Regge phenomenology, the strong interaction is due to the exchange of Reggeons which are characterised by their trajectory. At high energies, hadronic interactions are dominated by the exchange of an additional trajectory, the Pomeron. The energy dependence of the total hadronic cross section reflects therefore the interplay between Reggeon and Pomeron contributions. A three component fit yields good agreement with the existing data both for proton-proton and proton-antiproton cross sections in the range from $\sqrt{s} = 23$ GeV to $\sqrt{s} = 8$ TeV. Here, the three components are defined by the $f_2, a_2$, the $\rho, \omega$ and the Pomeron-trajectory [1].

Hadronic charge exchange reactions can only be due to the exchange of charged Reggeons, and are therefore of interest for testing the Regge prediction of their energy behaviour. The transfer of electric charge from one beam particle to a particle of the opposite beam is associated with bremsstrahlung radiation [2]. The theorem of Low relates the radiative leading and next-to-leading order in photon energy of the bremsstrahlung amplitude to the corresponding non-radiative amplitude [3]. The theorem of Low refers to soft photons, i.e. to photon energies which are smaller than any other momentum scale in the process. A study of photon emission in the high energy limit finds corrections in the next-to-leading radiative amplitude due to the internal structure of the external states [4]. The production of non-abelian gauge bosons and gravitons is studied as a generalization of the theorem of Low in Ref. [5].

REGGEON CHARGE EXCHANGE REACTION

In hadronic charge exchange reactions in proton-proton collisions, one or both of the beam particles can be excited to an $N^*$ or a $\Delta$-resonance. Here, the $N^*$ and $\Delta$-resonance represent the family of $N^*$ and $\Delta$-resonances as listed by the Particle Data Group [6].

\begin{align*}
pp & \rightarrow n + \Delta^{++} \quad \rightarrow \quad n + p \pi^+ \quad (1) \\
pp & \rightarrow \Delta^0 + \Delta^{++} \quad \rightarrow \quad p \pi^- + p \pi^+ \quad (2) \\
pp & \rightarrow \Delta^0 + \Delta^{++} \quad \rightarrow \quad n \pi^0 + p \pi^+ \quad (3)
\end{align*}

The charge exchange reactions 1)-3) listed above can be measured by identifying the forward scattered remnants of the resonance decay. In the following, only reaction 1) in the list above is discussed to illustrate the study of such reactions. The reactions 2) and 3) are the same, but are listed here separately due to the different final state produced by the decay of the $\Delta^0$-resonance into charged and neutral mode, respectively. The identification of the different decay channels necessitates not only the measurements of forward charged tracks, but also of very forward focussed neutral particles like neutrons and $\pi^0$. 
Cross section of Reggeon charge exchange reaction

The reaction 1) listed above was measured in a spark chamber experiment at the Argonne National Zero Gradient Synchrotron (ZGS) at a beam momentum of $P_{\text{lab}} = 6 \text{ GeV/c}$. The analysis of the data found good agreement with the basic Chew-Low one-pion-exchange mechanism yielding an energy dependence $\propto P_{\text{lab}}^{-2}$ [7]. Later experiments with the Split Field Magnet (SFM) at the Intersecting Storage Ring (ISR) at CERN extended the cross section measurement of this reaction to the energy range of $\sqrt{s} = 23$ to 53 GeV. The analysis of these data resulted in the conclusion that $\rho, a_2$-exchange is the dominating mechanism at the ISR-energies [8].

![Image](https://example.com/image.png)

**FIGURE 1.** Cross section data for $p p \rightarrow n \Delta^{++}$ (Figure taken from Ref. [7](left), [8](right)).

In Figure 1, the cross section for the charge exchange reaction $p p \rightarrow n \Delta^{++}$ is shown on the left for beam momenta $P_{\text{lab}} < 10 \text{ GeV/c}$. On the right hand side in Figure 1, the vertical axis is scaled with $P_{\text{lab}}^{-2}$. In this representation, the data points of pion-exchange dominated cross sections fall on a constant line. Clearly visible is the transition from pion to $\rho, a_2$-dominated exchange at a beam momentum which corresponds approximately to a centre-of-mass energy $\sqrt{s} \sim 23 \text{ GeV}$, i.e. the lowest energy at which data were taken at the ISR.

The cross section presented in Figure 1 above can be extrapolated to energies beyond the ISR measurements with the assumption of momentum scaling $\propto P_{\text{lab}}^{-1}$ corresponding to $\rho, a_2$-exchange.

**TABLE 1.** Cross section $p p \rightarrow n \Delta^{++}$.

| $\sqrt{s}(\text{GeV})$ | $\sigma(\text{nb})$     |
|------------------------|-------------------------|
| ISR                    |                         |
| 31                     | 580 $\pm$90             |
| 45                     | 210 $\pm$40             |
| 53                     | 170 $\pm$40             |
| RHIC                   |                         |
| 100                    | 48.5 $\pm$5.5           |
| 200                    | 12.2 $\pm$1.3           |
| LHC                    |                         |
| 7x10$^3$               | $(10.0\pm1.1)\times10^{-3}$ |
| 14x10$^3$              | $(2.4\pm0.3)\times10^{-3}$ |

In Table 1, the cross section values extrapolated to the RHIC and LHC energies are shown. For this extrapolation, the cross section values at the ISR energies of $\sqrt{s} = 31, 45$ and $53 \text{ GeV}$ and the quoted uncertainties were taken from Ref. [8], and fitted with a $\propto P_{\text{lab}}^{-1}$ dependence. The extrapolated cross section values are in the range of tens of nanobarns for the RHIC energies, whereas the values at the LHC energies are on the order of a few picobarns.

The characteristics of these events are very forward scattered beam remnants and a rapidity gap in between, i.e. a region in rapidity where no particles are produced. These events carry therefore the single gap topology of single and double-diffractive dissociation reactions. A double gap topology is also possible in hadronic charge exchange reactions. Here, two charged Reggeons fuse and produce a hadronic state at or close to mid-rapidity.
The double gap topology discussed above of forward beam remnants with activity in between can also be due to Weak-boson fusion (WBF) reactions. The study of such reactions is of interest for gaining insight into the electroweak gauge boson sector of the Standard Model. Such WBF-reactions are sensitive to the electroweak symmetry breaking mechanism, and hence are of high interest to improve the current understanding of this symmetry breaking.

\[
W^+ W^- p^* \rightarrow W^+ W^- p^* + H
\]

In Figure 2, the vector boson fusion diagram \( W^+ W^- \rightarrow X \) is shown on the left. In the middle, the diagram of interest for studies of quartic-couplings is displayed, whereas on the right, resonant WBF-production of Higgs is shown. A variety of different diagrams exist which can lead to the same final state. A careful study of these background channels is therefore mandatory to evaluate the signal to background ratio of WBF-measurements.

### Background single quark exchange

The background processes leading to the same final state as shown in Figure 2 consist of single and double quark exchange diagrams. The single quark exchange can be written as \( q q \rightarrow W^+ W^-, ZZ, \gamma \gamma \) plus additional parton exchange.

In Figure 3, the single quark exchange diagram is shown. A quark of one hadron annihilates with an anti-quark from the sea-distribution of the other hadron and emits a pair of \( W^+ W^- \), \( ZZ \) or photons.

### Background double quark exchange

The double quark exchange is expressed as \( q q q \rightarrow W^+ W^-, ZZ, \gamma \gamma \).

In Figure 4, the double quark exchange diagram is shown.
In the double quark exchange shown in Figure 4, two annihilation processes of a quark of one hadron with an anti-quark of the other hadron generate the two gauge bosons of the final state. In order to realistically evaluate the single and double-quark exchange background, the cross section needs to be known differentially as function of $p^+,0$ and $p^{+,2+}$, the invariant masses of the proton fragments. In addition, the phase space distribution of these fragments needs to be known accurately in order to evaluate the experimental acceptance of the forward scattered proton remnants.

**EXPERIMENTAL CONSIDERATIONS**

The experimental measurement of the charge exchange reactions discussed above is in principle possible by identifying charge asymmetric forward systems with $Z_{tot} = 0$ and $Z_{tot} = 2$ at the two opposite sides, respectively. The difference of these forward charges, $\Delta Z_{tot} = 2$, constitutes a parameter for selecting the charge exchange events. Such measurements require, however, forward detector systems with excellent acceptance. The missing of one charged track would change $\Delta Z$ by one unit, but would still suffice to recognize a forward charge asymmetry. The missing of two forward charged tracks would, however, introduce considerable uncertainty. If the two tracks are of like-sign charge and missed on opposite sides, or of unlike-sign charge and missed on the same side, then the charge asymmetry would not change. If the two tracks are of like-sign charge and missed on the same side, or of unlike-sign charge and missed on opposite sides, then the charge asymmetry would change by two units with resulting values of $Z_{tot} = 0$ or 4, respectively. The building and installation of forward detector systems with close to perfect acceptance for charged tracks is, however, a considerable challenge from the experimental viewpoint. Such systems are presently not in operation or under discussion neither at RHIC nor at the LHC.

**SUMMARY**

The cross section of the charge exchange reaction $pp \rightarrow n \Delta^{++}$ is expected to follow an approximate $\propto p_{lab}^{-1}$ dependence at high energies as seen in the data taken at the ISR-energies. The precise measurement of this cross section at energies beyond the ISR energies would allow to test the individual contributions from $\rho$ and $a_2$-exchanges due to their different energy dependence. The study of charge exchange by WBF-reactions necessitates a careful evaluation of the signal and of the background resulting from single and double-quark exchange diagrams. In order to optimize the signal to background ratio, the phase space distribution of the forward proton fragments needs to be known both for signal and background. The forward charge asymmetry of charge exchange reactions defines a parameter which can be used to select such events. The accurate measurement of this charge asymmetry poses, however, a considerable challenge to the experimenters, and has so far not been considered.

**ACKNOWLEDGMENTS**

The author gratefully acknowledges fruitful discussions with J. Bartels, L. Jenkovszky, L. Lipatov and R. Pasechnik on the issues presented here. This work is supported by the German Federal Ministry of Education and Research under promotional reference 05P12VHCA1 and by WP8 of the hadron physics programme of the 7th EU programme period.

**REFERENCES**

1. A. Donnachie, and P. V. Landshoff, *Phys. Lett. B* **727**, 500–505 (2013).
2. J. D. Jackson, *Classical Electrodynamics*, John Wiley & Sons, New York, 654–678 (1975).
3. F. E. Low, *Phys. Rev.* **110**, 974–977 (1958).
4. V. Del Duca, *Nucl. Phys. B* **345**, 369–388 (1990).
5. L. N. Lipatov, *Nucl. Phys. B* **307**, 705–720 (1988).
6. K. A. Olive et al., (Particle Data Group), *Chin. Phys. C* **38**, 090001 (2014).
7. J. D. Mountz et al., *Phys. Rev. D* **12**, 1211-1218 (1975).
8. H. De Kerret et al., *Phys. Lett. B* **69**, 372–376 (1977).