NONPERTURBATIVE EFFECTS IN THE PROTON SEA

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We revisit the evaluation of the pionic mechanism of the $\bar{u} - \bar{d}$-asymmetry in the proton structure function. Our analysis is based on the unitarity relation between contributions of different mechanisms to the inclusive particle production and the total photoabsorption cross-section (i.e. the proton structure function). We reanalyze the role of isovector reggeons in inclusive production of nucleons and Delta isobars in hadronic reactions. A rather large contribution of reggeon-exchange induced production of Delta isobars is found. This leaves much less room for the pion-exchange induced mechanism of $\Delta$ production and provides a constraint on the $\pi N\Delta$ form factor. The production of leading pions in proton-proton collisions puts additional constraints on the $\pi N\Delta$ vertex form factors. All these constraints are used then to estimate the pion content of the nucleon and allow to calculate parameter-free the $x$-dependence of $\bar{d} - \bar{u}$. We discuss the violation of the Gottfried Sum Rule and $\bar{d} - \bar{u}$ asymmetry and compare to the one obtained from the E866 experiment at Fermilab.

1 Introduction

Since the discovery of the Gottfried sum rule violation there has been a long ongoing discussion on the $\bar{d} - \bar{u}$ asymmetry in the nucleon sea. Considerable attraction has been received recently by the E866 experiment at Fermilab, which provided the first detailed measurement of the Bjorken–$x$ dependence of the $\bar{d} - \bar{u}$–asymmetry from the comparison of $pp$ and $pd$ Drell–Yan production. Their striking finding is that the asymmetry tends to vanish at $x \sim 0.3$.

The strong observed asymmetry has no explanation in terms of the purely pQCD dynamics, and thus it gives important hints on the impact of the nonperturbative proton structure on the generation of the nucleon’s sea quark content. Following the early work of Sullivan, a natural dynamical explanation emerges within the framework of the isovector meson cloud model of the nucleon (for a recent review see). Here a special role is played by the pion, and it is intuitively appealing to account for the nonperturbative meson/baryon structure of the proton, by including the pion as the nonperturbative parton in the light cone wave function of the interacting nucleon:

$$|N\rangle_{\text{phys}} = |N\rangle_{\text{bare}} + |N\pi\rangle + |\Delta\pi\rangle + \ldots.$$  (1)

Here the pion, that is contained in the $N\pi, \Delta\pi$–Fock states can emerge as the target in the deep inelastic $\gamma^*N$ photoabsorption process, while the spectator
baryonic constituent $N, \Delta$ appears in the final state, separated from the remnants of the $\gamma^* \pi$-interaction by a rapidity gap and carrying a large fraction $z$ of the incoming proton's lightcone momentum. Hence, inclusive production of baryons, like $\gamma^* p \rightarrow X n$ is naturally described in terms of the pionic 'partons' in the nucleon. But precisely the same dynamics is supposed to be at work, if we swap the virtual photon against the proton projectile. This opens the possibility to use a large body of experimental knowledge on inclusive particle production in hadronic reactions to constrain the meson/baryon dynamics relevant for deep inelastic scattering. In the following we shall demonstrate, that if one accounts consistently for the so-derived constraints, a satisfactory description of the Fermilab data emerges.

2 Inclusive production of baryons and mesons in hadronic reactions

2.1 Production of forward neutrons and $\Delta$-isobars

Following the above described strategy, we first turn to the description of the forward neutron production in $pp$ collisions. We take into account three production mechanisms: the dominant pion exchange, the background contribution from the isovector exchanges $\rho, a_2$, and, finally, the production of neutrons from the decay of an intermediate $\Delta$-resonance (see fig 1). In addition, we have to account for the distortion of the incoming proton waves, employing standard methods of the generalized eikonal approximation. Following the reasoning in, we apply the absorptive corrections only in the $pp$ scattering, they can be neglected in the $\gamma^* p$-case. It is important to notice, that the phase space
of the forward neutrons includes the kinematical boundary \( z \sim 1 \), which corresponds to a large Regge parameter \( s/M_X^2 \gg 1 \), where \( M_X^2 \) is the invariant mass squared of the inclusive system \( X \). Hence the proper formalization of the \( \rho \)-exchange mechanism should be a Regge treatment.

In the Regge formulation, the contribution to the inclusive cross section from the pion exchange mechanism has the form:

\[
\frac{d\sigma(p \to n)}{dzdp_\perp^2} = \frac{g_{\pi pn}^2}{16\pi^2} \frac{(-t)}{|t - m_\pi^2|^2} \cdot F_{\pi NN}^2(t)(1 - z)^{1-2\alpha_\pi(t)} \cdot \sigma_{tot}^\pi(M_X^2),
\]

(2)

with \( -t = p_\perp^2/z + (1 - z)^2m_p^2/z \), \( z \) is the neutrons Feynman–variable, which for large \( z \) is equal to its lightcone momentum fraction, \( p_\perp \) is the neutron’s transverse momentum. Due to the proximity of the pion pole, the departure of \( \alpha_\pi(t) = \alpha'(t - m_\pi^2) \), \( \alpha' \approx 0.7 \text{GeV}^{-2} \) from \( J_\pi = 0 \) is small, and we can justify taking the physical pion–nucleon cross section \( \sigma_{tot}^\pi \). The finite extension of the involved particles and/or the off shell effects are accounted for by the form factor \( F_{\pi NN}^2(t) \), in the following we shall stick to the parametrization: \( F_{\pi NN}^2(t) = \exp[(R^2(t - m_\pi^2))^2], R^2 \approx 1.5 \text{GeV}^{-2} \), for different choices of the functional form, see the discussion in.

In fig. 2 we show our results for the invariant cross section against the experimental data. The data shown here are at relatively low \( p_{LAB} \approx 24 \text{GeV}/c \), hence the visible trace of the \( \pi N \)–resonance–region at large \( z \). The \( p_\perp \)–dependence nicely illustrates the interplay of the different mechanisms. The pion exchange peaks in the region \( 0.7 \lesssim z \lesssim 0.9 \), and dominates for \( p_\perp \sim 0.3 \text{GeV} \).

The relative importance of the \( \rho, a_2 \) exchanges grows with \( p_\perp \), which testifies to the dominant \( \propto p_\perp^2 \) spin–flip component of the \( \rho N \)–coupling. The background contribution from the two–step process \( p \to \Delta \to n \) turns out to be substantial only for \( z \lesssim 0.8 \).

We took care that the background from the \( \Delta \)–decay is consistent with the experimental data on forward-\( \Delta \)–production, to which we turn now. Unfortunately, experimental data are rather scarce, and often plagued by large uncertainties due to the nonresonant \( \pi N \) subtraction. We do not have any data differential in \( p_\perp \) at hand, and obviously the shape of the \( p_\perp \)–integrated \( \Delta \)–spectrum could be fitted by both extreme choices: the pure \( \pi \)-exchange as well as the pure \( \rho \)-exchange. Here valuable information comes from the two–body reactions at high energies. The cleanest manifestation of \( \rho \)-exchange is clearly the \( \pi N \)–charge exchange reaction \( \pi^- p \to \pi^0 n \) and \( \pi^+ p \to \pi^0 \Delta^{++} \), for which experimental data are available. Assuming Regge factorization, we can now relate the \( \rho \)-exchange contribution in the \( p \to n \) transition from our earlier considerations to the \( \rho \)-exchange in \( p \to \Delta \). The result is a surprisingly large \( \rho \)-exchange contribution, which does not leave much room for the pionic

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contribution (see fig 3.).

Figure 2: Invariant cross section for the reaction \( pp \rightarrow nX \) at \( p_{LAB} = 24 \text{ GeV/c} \). The experimental data are taken from 9. The long dashed curve shows the contribution from the pion exchange; the dotted curve is the \( \rho, \omega \)-exchange contribution, and the dashed curve shows the contribution from the two step process \( p \rightarrow \Delta \rightarrow n \). In addition, we present the sum of the two background contributions as the dot-dashed line. Finally, the solid curve represents the sum of all components.

2.2 Constraints from forward pion production

The good description of the forward baryon production can make us confident, that we have found a proper description of the \( \pi N, \pi \Delta \)-fock states in the region where the baryon carries a large momentum fraction \( z \sim 0.6 \div 1 \). However, we should be aware, that the forward baryon production data do not put any constraint on the region \( z \lesssim 0.6 \); in such a kinematical region we cannot expect the meson/Reggeon exchanges to be the dominant reaction mechanisms. On the other hand, in the Fock–state picture a baryon carrying a small momentum fraction \( z_B \ll 1 \) is accompanied by the meson carrying large \( z_M = 1 - z_B \sim 1 \). Hence, the natural place to check the consistency of the Fock–state parameters is the production of forward, \( z_\pi \sim 1 \), pions. The important message from the experimental data (fig.4) is: there are \textit{no pions carrying large momentum fractions} \( 0.6 \lesssim z \lesssim 1 \) observed. This places a severe constraint on the cutoff in the employed \( \pi NN \)-formfactor. (Notice that we are not after a description of the forward pion production for \( z \lesssim 0.5 \).) The specific formfactor choice cited
Figure 3: Differential cross section $d\sigma/dz$ for the reaction $pp \rightarrow \Delta^{++}X$ at $p_{LAB} = 400$ GeV/c. The dashed curve is the contribution from pion-exchange; the dotted curve shows the $\rho, a_2$ contribution. Shown by the solid curve is the sum of the two. Experimental data are taken from (open circles), and (filled circles).

above leads to the middle solid curve in fig.4. Incidentally, the dotted line on fig.4 shows the result of a previously employed formfactor that also did a reasonable job on forward neutrons, but does not respect the pion production data.

3 Regge mechanisms vs. Fock–state picture

In the introduction we stressed the relevance of the pion as the nonperturbative parton in the light–cone wave function of the interacting proton. Here the question arises what kind of Fock–state should then be associated with the $\rho, a_2$-Reggeon exchange production mechanisms, if any? In other words, knowing the reaction mechanisms that populate several inclusive channels, what can we say about their impact on the total cross section? We remind, that one of the firm predictions of Regge theory is a very specific phase of the amplitudes. While the inclusive cross section is calculated from the modulus of the amplitude squared, $|A|^2$, it is the product of two amplitudes, $A \cdot A$, that enters the evaluation of the total cross section. The result may be summarized by generalized AGK cutting rules: for the purely real pion exchange amplitude, this implies that inelastic interactions of the projectile with the pions in the target hadrons enhances the total cross section, whereas the $\rho, a_2$–exchanges, which have a phase $\sim (1 + i)$, happen to give a vanishing contribution to the total cross section. Hence, it does not make any sense, to identify the Reggeon ex-
change mechanism in inelastic reactions in terms of a meson/baryon–Fock state of the proton. We want to point out that there is no mystery connected with such a different impact of the phases on different observables. For instance in the inclusive reaction $pp \rightarrow pX$, diffractive channels (imaginary amplitude) dominate for $z \sim 1$, and it is well known that the opening of diffractive channels comes along with the absorptive correction to the total cross section, which is negative.

4 The $\bar{d} - \bar{u}$ asymmetry from pions in the nucleon

Following our reasoning above, we include the $\pi N$, $\pi \Delta$– Fock states only. They lead to a contribution to the total $\gamma^* p$–cross section – i.e. the quark/antiquark–distributions in the proton given by

$$\Delta^\pi q(x, Q^2) = \int_x^1 \frac{dz}{z} f_\pi(z) \cdot q^\pi(x/z, Q^2),$$

with the flux of pions which is determined through

$$f_\pi(z) = \int d^2\vec{p}_E \frac{d\sigma(p \rightarrow n)}{\sigma_{tot} d^3p},$$
and similarly for the $\pi\Delta$–Fock state. Besides the Fock–state parameters determined in our analysis above, we need as an input the quark distributions in the pion. Notice, that for the calculation of $\bar{d}(x) - \bar{u}(x)$ only the pion’s valence distributions enter. These are reasonably well constrained down to $x \sim 0.2$ from the Drell–Yan experiments, for definiteness we take the GRV–parametrization. We obtain a total multiplicity of pions in the proton associated with the $\pi N$–state of $n_{\pi N} \sim 0.21 \div 0.28$ and of $n_{\pi \Delta} \sim 0.03 \ll n_{\pi N}$ for the $\pi\Delta$–contribution. This translates to a Gottfried sum of $0.21 \lesssim S_G \lesssim 0.25$, compared to the NMC determination $S_G = 0.235 \pm 0.026$. Our result for $\bar{d} - \bar{u}$ is shown in fig 5, we observe that the asymmetry is essentially driven by the $\pi N$–state. Notice that our good agreement in the region $x \gtrsim 0.2$ owes to the fact that we have no contributions from hard $z_\pi \gtrsim 0.5$ pions in the nucleon.

5 Summary

Our reanalysis of the pionic contribution to the $\bar{d} - \bar{u}$– asymmetry has been based on a unified treatment of the inclusive production of leading nucleons, $\Delta$’s and pions in hadronic high energy collisions. We paid special attention to the background contributions in the leading baryon production, and clarified the relation of Reggeon–exchange mechanisms and the Fock–state picture of the interacting nucleon. Severe constraints on our parameters were found to arise from the forward pion data. A good agreement with the recent E866 data on $\bar{d} - \bar{u}$ was found.

Finally we want to point at another spin–off of our analysis: namely one may use the pions in the nucleon as targets in deep inelastic scattering and hence obtain information on its structure function at small $x$, unexplored by the Drell-Yan experiment. Our findings for the relevant background contributions show that this task is well feasible.

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Figure 5: Flavour asymmetry $d(x) - \bar{u}(x)$ at $Q^2 = 54$ GeV$^2$. Experimental data are from E866. The solid curves show the contribution from the $\pi N$-Fock state and were calculated for Gaussian form-factors; the upper curve belongs to $R_G^2 = 1$ GeV$^2$, the lower one to $R_G^2 = 1.5$ GeV$^2$. The dashed line shows the contribution of the $\pi\Delta$-Fock state.

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