Pion Content of the Nucleon as seen in the NA51 Drell-Yan experiment

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Abstract

In a recent CERN Drell-Yan experiment the NA51 group found a strong asymmetry of $\bar{u}$ and $\bar{d}$ densities in the proton at $x \approx 0.18$. We interpret this result as a decisive confirmation of the pion-induced sea in the nucleon.
With the advent of high precision data on deep inelastic scattering, understanding of the nonperturbative flavour structure of the nucleon is becoming one of the pressing issues where the interests of particle and nuclear physics converge. At large $Q^2$ the perturbative QCD evolution is flavour independent and, to leading order in $\log Q^2$, generates equal number of $\bar{u}$ and $\bar{d}$ sea quarks. The $\bar{u} - \bar{d}$ asymmetry coming from effects of the interference between the $u$ and $d$ quarks from the perturbative sea $\bar{u}u$ and $\bar{d}d$ pairs and the valence $u$ and $d$ quarks of the nucleon was found to be negligible [1]. Perturbative QCD describes only the $Q^2$-evolution of deep inelastic structure functions starting with certain nonperturbative input. There are no a priori reasons to expect a $\bar{u} - \bar{d}$ symmetric nonperturbative sea. Furthermore, the strong correlations between quarks and antiquarks of the nonperturbative sea, exemplified by the pionic field in physical nucleons, leads to precisely such an asymmetry [2–8]. There is already experimental evidence for such an asymmetry from the Gottfried Sum Rule violation observed by the NMC collaboration at CERN [9].

In the simplest models the nucleon is treated as a system of three quarks. The pion-nucleon interaction leads naturally to an admixture of a $\pi N$ Fock component in the physical nucleon. In the simplest approximation, the Fock state expansion of the light cone proton reads (shown are the probabilities of the different components):

$$|p\rangle_{\text{phys}} = \frac{1}{Z}
\left[
|p\rangle_{\text{core}} + n_\pi \left(\frac{1}{3} |p\pi^0\rangle + \frac{2}{3} |n\pi^+\rangle\right)\right]$$

(1)

with $Z$ being the wave function renormalization constant defined by $Z = 1 + n_\pi$. Here $n_\pi/Z$ gives the probability to find the physical proton in a light cone Fock state consisting of a nucleonic core and a pion.

The $\pi_0$ quark distributions are symmetric functions of up and down quarks. The quark content of the $\pi^+ = u\bar{d}$ implies, however, that $\bar{u} < \bar{d}$. Recently the CERN NA51 collaboration [10] presented the first direct measurement of the $\bar{u}/\bar{d}$ asymmetry

$$\frac{\bar{u}(x)}{d(x)} = 0.56 \pm 0.04 \pm 0.05 \quad \text{at} \quad x = 0.18.$$  

(2)

In this paper we interpret the NA51 result as decisive evidence for the pion induced nonperturbative sea in the nucleon.
Before the NA51 result, the experimental evidence for any $\bar{u} - \bar{d}$ asymmetry came from an analysis of the Gottfried-Sum-Rule (GSR) violation \[1\], which in the Quark-Parton-Model can be related to

$$GSR = \int_0^1 [F_2^p(x) - F_2^n(x)] \frac{dx}{x} = \frac{1}{3} + \frac{2}{3} \int_0^1 [\bar{u}(x) - \bar{d}(x)] \, dx.$$ \hspace{1cm} (3)

Experimentally, the determination of $F_2^n$ is biased by the uncertainties because of the nuclear shadowing effects at small $x < x_{shad} \simeq 0.05$ \[11,12\]. Furthermore, the GSR analysis gives only the integrated asymmetry, and does not identify the region of $x$ from which the asymmetry comes. Different dynamical models predict a $\bar{u}/\bar{d}$ asymmetry concentrated in different regions of $x$. In this paper we wish to emphasize that $x \simeq 0.2$ is the region where the nucleon sea is expected to be dominated by the nonperturbative pion-induced sea.

The NA51 analysis is based on the comparison of the Drell-Yan dilepton pair production in $pp$ and $pn$ collisions. Here, one can kinematically select annihilation of the valence quarks in the projectile proton and the sea quarks of the target nucleon. Since the valence quark distributions are fairly well known, one can extract the $\bar{u}/\bar{d}$ asymmetry \[13–15\]. In order to extract the $pn$ cross section, the NA51 experiment used a deuteron target, but $x \simeq 0.2$ is a region free of the shadowing effects.

Ever since the observed violation of the GSR, there were attempts to accomodate the GSR-implied $\bar{u}/\bar{d}$ asymmetry into the QCD evolution analysis of nucleonic structure functions. Usually the asymmetry is introduced in terms of plausible parametrizations and, depending on the parametrization, the asymmetry can be placed either in the large-$x$ or small-$x$ region, reflecting one’s prejudice about where the violation of the GSR comes from. As an example we will present the $\bar{u}/\bar{d}$ ratio using the Martin-Stirling-Roberts parametrization \[16\]$(D_0', D'_\perp)$, which was fitted to the previously available data on deep inelastic scattering and Drell-Yan dilepton production. Due to the functional form of the parametrization employed, this fit implicitly assumes that the $\bar{u} - \bar{d}$ asymmetry is concentrated in the small $x$ region. We also show predictions from the model of the pion induced sea which is in a good agreement with the NA51 result \[10\]. Below we describe the corresponding calculation.
in more detail.

The pionic corrections to the quark distributions of the physical nucleon are given by the convolution formula

\[
q_{p,\text{phys}}(x) = \frac{1}{Z} \left[ q_{p,\text{core}}(x) + \int_x^1 n_\pi(1-y) \left( \frac{1}{3} q_{p,\text{core}}(\frac{x}{y}) + \frac{2}{3} q_{n,\text{core}}(\frac{x}{y}) \right) \frac{dy}{y} \right. \\
+ \left. \int_x^1 n_\pi(y) \left( \frac{1}{3} q_{\pi^0}(\frac{x}{y}) + \frac{2}{3} q_{\pi^+}(\frac{x}{y}) \right) \frac{dy}{y} \right].
\]

(4)

The function \( n_\pi(y)/Z \) (for formulas see [5,17]) gives the probability that the physical proton is in the virtual 'nucleonic core'-meson state with the meson carrying a longitudinal momentum fraction \( y \) of the proton momentum. Thus, \( n_\pi(1-y)/Z \) is the probability that the corresponding nucleonic core carries a longitudinal momentum fraction \( y \). Remarkably enough, the number of pions \( n_\pi \) and the \( \bar{u} - \bar{d} \) asymmetry can be calculated essentially parameter-free using pion-nucleon interaction parameters inferred from low- and high-energy soft hadronic interactions [5,7,17,8]. Specifically, the pion-exchange contribution enters the high energy nucleon (delta) production in hadronic reactions (Fig.1a) and the lepton deep inelastic scattering off virtual pions (Fig.1b) in similar kinematical conditions. Both processes are described by the same light cone \( \pi N \) wave function, which allows one to constrain the principal parameters, the radii of the meson-baryon light cone wave functions, from an analysis of the \( p \to n, \Lambda, \text{etc.} \) fragmentation spectra [8]. The formulas for the meson-baryon splitting functions and the parameters needed for the analysis (coupling constants, radii of the light cone meson-baryon Fock states) can be found elsewhere [5,17,8]. This model can easily be extented to include other, important Fock components. The full model [6,8] includes all octet and decuplet baryons, as well as the pseudoscalar and vector mesons.

In order to make predictions for the sea quark distributions, one needs input for the \( q \) \((\bar{q})\) distributions of the pion (mesons). Fortunately enough, in the region of interest, the meson induced sea is dominated by the valence quarks of the pion. Indeed, typically \( n_\pi(y) \) has a maximum at \( y \simeq 0.3 \) and the \( x = 0.18 \) studied in the NA51 experiment corresponds to the rather large Bjorken variable in deep inelastic scattering off pions \( x_\pi \simeq x/y \simeq 0.6 \). Thus, the recent parametrization [8] based on the \( \pi N \) Drell-Yan data can be regarded as
reliable and the meson-induced sea can be calculated with good accuracy. We assume the same parametrization to hold also for vector mesons.

The primordial sea distribution of the nucleonic core is poorly known. One cannot use here the conventional parametrizations which implicitly contain the mesonic effects. We adopt the following phenomenological procedure. We assume the primordial sea in the nucleonic core to be $\bar{u}$-$\bar{d}$ symmetric. For the shape of the primordial sea we take the symmetric MRS ($S'_0$) [16] parametrization. Then the MSR distribution is multiplied by a rescaling factor to obtain rough agreement with the absolute normalization of the MRS($D'_0$, $D'_-$) [16] $\bar{u}$ and $\bar{d}$ distributions. Such a procedure suggests that the primordial sea is about 50% of that given by the symmetric MRS ($S'_0$) parametrization. The procedure is somewhat crude since the ($D'_0$, $D'_-$) parametrization does not reproduce the NA51 result, and this comparison suggests a primordial sea which is somewhat steeper than given by the MSR ($S'_0$) parametrization. But as we shall see, in the region of interest the effect of the primordial sea is actually a correction.

The result of our calculation for the $\bar{u}/\bar{d}$ ratio is shown in Fig.2. The solid line shows our prediction using the full model. The decomposition of the $\bar{u}(x)$ and $\bar{d}(x)$ distribution into contributions from different mechanisms is shown in Fig.3. As seen from the figure, the contribution of the $\pi N$ component to $x\bar{d}$ is significantly larger than to $x\bar{u}$. The source of this difference is the valence quark distribution of the $\pi^+$. This is our main source of the $\bar{u}$-$\bar{d}$ asymmetry. Also the $\rho N$ component (not shown separately in Fig.3) introduces the asymmetry. The other components ($\pi\Delta$ and $\rho\Delta$) dilute the asymmetry; because of the isospin 3/2 of the $\Delta$, they generate more $\bar{u}$ than $\bar{d}$ quarks. Small contributions from the hyperon–strange meson Fock states are also included. The sensitivity of our results to the size of the primordial sea can be seen from Fig.2 (dashed lines), where we also show the $\bar{u}(x)/\bar{d}(x)$ ratio with drastically different reduction factors: 0.25 - dashed curve and 0.75 - dot dashed curve. As can be seen from the figure, the resulting asymmetry is quite insensitive to the reduction factor. For comparison we also show $\bar{u}/\bar{d}$ ratio obtained from the MSR ($D'_0$, $D'_-$) parametrizations [16]. In the present approach, an absolute normalization of
the meson-induced sea is based on the combined description of deep inelastic and hadronic
termination processes of Fig.1 using the same light cone wave function. The absorption
corrections in both processes may be different, but their overall effect is known to be nu-
merically small, < 10-20% \[19\]. They suppress the hadronic reaction cross section, which
may lead to a slight underestimation of the meson-induced sea in our calculation.

The quark distributions in Figs.2 and 3 have been calculated at the momentum scale
\[ Q^2 = 4 \text{ GeV}^2 \]. The QCD evolution to the region of \[ Q^2 = 10-20 \text{ GeV}^2 \], appropriate for the
NA51 Drell-Yan data, has a negligible effect on the \[ \bar{u}/\bar{d} \] ratio shown in Fig.2.

Summarizing, the new NA51 result \[ \bar{u}/\bar{d} = 0.56 \pm 0.04 \pm 0.05 \text{ at } x = 0.18 \] can naturally
be explained by the presence of \( \pi(\rho) - \text{baryonic core} \) Fock components in the nucleon wave
function. The observed asymmetry can, in principle, be reproduced by suitably modified
parametrizations which allow for stronger asymmetry placed at somewhat larger \( x \) compared
to the MSR \( D_0', D^{-}_0 \) parametrizations \[14\]. We emphasize that, in contrast to parametriza-
tions, our results are predictions from a dynamical model which predicts nonperturbative sea
distributions without free parameters. Furthermore, our model of the nucleon makes a link
between low energy meson-nucleon couplings, high energy soft hadron-hadron collisions and
hard deep inelastic scattering of leptons. It is worth mentioning here that a recent lattice
QCD calculations gave evidence for the importance of pion loop effects for nucleon proper-
ties \[20\]. New experiments at larger \( x \) are neccessary to give more insight into the pionic (or
more general: mesonic) cloud of the nucleon. The definite prediction of the meson-induced
sea model is that the \( \pi N \) and \( \rho N \) Fock components dominate the antiquark distributions
in the large \( x \) region. Consequently, the \( \bar{u}/\bar{d} \) ratio is predicted to decrease towards \( 1/5 \) at
\( x \rightarrow 1 \). Unfortunately the predictive power of the model deteriorates close to the kinemat-
tical limits of \( y \rightarrow 1 \) and \( y \rightarrow 0 \), where the meson-baryon light cone wave function is not
well known. The new experiment planned at Fermilab \[14\] will be useful in this respect and
should provide a possibility of pinning down the \( x \) dependence of the \( \bar{u} - \bar{d} \) asymmetry up
to \( x = 0.4 \).
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FIGURES

FIG. 1. The diagrams for high energy nucleon(delta) production in a hadron-nucleon collision (a) and the deep inelastic scattering off virtual pion (b).

FIG. 2. The $\bar{u}(x)/\bar{d}(x)$ ratio measured by the Drell-Yan NA51 group compared to: the experimental $D'_0$ (dotted) and $D'_-$ (double-dotted) MSR parametrizations [16], and our full model (solid). In addition we show the result with the primordial sea contribution in baryons reduced by a factor 0.25 (dashed) and 0.75 (dot-dashed).

FIG. 3. The contributions of various Fock states to the $x\bar{u}$ (Fig. 3a) and $x\bar{d}$ (Fig. 3b) distributions. The dotted curves correspond to the asymmetric quark distributions $D'_0$ (dotted), $D'_-$ (double-dotted) from Ref. [16].
