On the Interpretation of the NA51 Experiment

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Abstract

We study the $p-n$ Drell-Yan asymmetry, recently measured by the NA51 collaboration, and conclude that the value quoted by their experiment only sets a lower limit on the asymmetry of the proton sea. In particular, we notice that charge symmetry breaking between the proton and the neutron may produce corrections which should be taken into account.

The confirmation by the New Muon Collaboration (NMC) [1] of an earlier hint in SLAC data [2] of a sizeable violation of the Gottfried sum-rule [3] has stimulated enormous interest in the flavour structure of the parton distributions [4]. Early theoretical work by Feynman and Field [5] had suggested that the Pauli Exclusion Principle may lead to $d > u$, a result supported by calculations using the MIT bag model [6]. However, most of the work aimed at interpreting the NMC results has been based on the role the pion cloud of the nucleon, which as first noted in 1983, predicts $\overline{d} > \overline{u}$ [7].

Of course, the interpretation of the NMC results in terms of a violation of flavour symmetry in the sea is not unambiguous. One must correct for shadowing and meson cloud contributions in the deuteron in order to extract the neutron structure function. Nevertheless, there seems to be a consensus that these corrections enhance the violation of the GSR a little [8]. It has also been suggested that the violation may be merely apparent, because the expected Regge behaviour at small-$x$ may set in less rapidly than is usually
assumed \[1\]. In any case, it is very important to look for other means to test whether in fact \( \bar{d} > \bar{n} \).

Some time ago, the NA51 group [10] released a measurement of the \( p-n \) cross section asymmetry defined as

\[
A_{DY}(x) = \frac{\sigma^{pp}(x) - \sigma^{pn}(x)}{\sigma^{pp}(x) + \sigma^{pn}(x)}. \tag{1}
\]

This experiment followed a suggestion by Ellis and Stirling [11] where it was argued that the sign and the size of \( A_{DY} \) can tell whether the sea is symmetric in flavour or not. This would be possible because \( \sigma_{pN}(x) \propto \sum_i e_i^2 q_i^p(x)q_i^N(x) + q_i^p(x)q_i^N(x) \) and then \( A_{DY} \) can be expressed as:

\[
A_{DY}(x) = \left\{ (4 \lambda_v(x) - 1)(\lambda_s(x) - 1) + (\lambda_v(x) - 1)(4 \lambda_s(x) - 1) \right\} / \left\{ (4 \lambda_v(x) + 1)(\lambda_s(x) + 1) + (\lambda_v(x) + 1)(4 \lambda_s(x) + 1) \right\}
+ 2d(x)(4 \lambda_s(x) + 1)(\lambda_s(x) + 1)/d_v(x) \tag{2}
\]

with \( \lambda_v(x) = u_v(x)/d_v(x) \) and \( \lambda_s(x) = u_s(x)/d(x) \). For completeness, we have included sea-sea corrections in Eq. (2). It is then clear that for a sea which is SU(2) flavour symmetric, i.e. \( \lambda_s = 1 \), the asymmetry is always positive if \( \lambda_v \) is larger than unity. On the other hand the asymmetry can change sign for \( \lambda_s \neq 1 \). In particular, if \( \lambda_v = 2 \) the asymmetry is negative for \( \lambda_s < 0.72 \) - where, for simplicity, the last term (the sea-sea term) was neglected. However, the important feature of the \( p-n \) cross section asymmetry is that, given a value for \( \lambda_v \), the measured asymmetry determines whether or not there is any sort of isospin breaking. In this letter we will explore the idea that the measurement of \( A_{DY} \) is not enough to precisely determine \( \lambda_s \) and thus the degree of asymmetry in the quark sea, as has been claimed [10, 11]. This point will be clear from expression (3), where possible corrections from charge symmetry breaking between the neutron and the proton at a given \( x \) are included.

The NA51 collaboration quoted the following result [10]:

\[
A_{DY}(x = 0.18) = -0.09 \pm 0.02(stat) \pm 0.025(syst) \tag{3}
\]

from which they derived
\[ \lambda_s(x = 0.18) = 0.51 \pm 0.04(stat) \pm 0.05(syst), \quad (4) \]

where sea-sea corrections were included but nuclear effects were left out. In this interpretation, the experiment indicates that there is a strongly asymmetric sea at \( x = 0.18 \). We are now going to show that, in fact, the \( \lambda_s \) quoted in Eq. (4) is only a limiting value set within the framework of Eq. (2) which was based on the assumption of charge symmetry (e.g. \( \bar{u}^p(x) = d^n(x) \) and \( \bar{d}^p(x) = \bar{u}^n(x) \)). We could as well have set the sea to be flavour symmetric and derived the following expression for the Drell-Yan asymmetry:

\[
A_{DY}(x) = \frac{\{3(\lambda_v(x) - 1) - (1 + 4\lambda_v(x))\bar{\delta}(x)/\bar{\tau}(x) + 3\delta(x)/d_v(x) - 10\bar{\delta}(x)/d_v(x)\}}{\{13\lambda_v(x) + 7 + (4\lambda_v(x) + 1)\bar{\delta}(x)/\bar{\tau}(x) - 3\delta(x)/d_v(x) + 10\bar{\delta}(x)/d_v(x) + 20\bar{\tau}(x)/\bar{\tau}(x)\}}. \quad (5)
\]

Here, we used \( \bar{\tau}(x) = \bar{\mu}(x) = \bar{d}^v(x) - \bar{\delta}(x), \bar{d}(x) = \bar{d}^p(x) = \bar{u}^v(x) - \bar{\delta}(x) \), \( u_v(x) = u^p_v(x) = d^n_v(x) - \delta(x) \) and \( d_v(x) = d^p_v(x) = u^n_v(x) + \delta(x) \). The function \( \delta(x) \) does not need to be the same for \( u_v \) and \( d_v \) but we use the same function to simplify the expressions as we illustrate the main idea. Also notice that different signs are used for the corrections in \( d^n_v \) and \( u^n_v \) as this seems to be suggested by theoretical evidence [12]. We have also considered the case where both signs coincide and the conclusions presented here are insensitive to such a choice. Of course, \( \int_0^1 dx \delta(x) = 0 \) to preserve the number of valence quarks. Using the experimental result for \( A_{DY}(x) \), we can estimate the amount of charge symmetry breaking.

For that purpose, we will work with the MRS parametrization, \( S_0' \), for \( \bar{\tau}(x), u_v(x) \) and \( d_v(x) \). In this parametrization the sea is symmetric and, for \( x = 0.18 \), \( Q^2 = (5.22 \text{ GeV})^2 = x^2s \) for \( s = (29 \text{ GeV})^2 \) the square of the center of mass energy of the NA51 experiment, it gives \( \bar{\tau}(x = 0.18) = 0.348, u_v(x = 0.18) = 3.13 \) and \( d_v(x = 0.18) = 1.486 \). From the experimental result quoted in Eq. (3) we then obtain:

\[
\bar{\delta}(x = 0.18) = 0.2088 - 0.0933\delta(x = 0.18). \quad (6)
\]
In calculating Eq. (6) we disregarded the sea-sea correction term \((20\overline{q}(x)/d_v(x))\) and took only the central value of the measured asymmetry. This is a good approximation as, using the same procedure when recalculating result (4), we get \(\lambda_s(x = 0.18) \simeq 0.53\). Eq. (6) tells us that the interpretation of the Drell-Yan asymmetry purely in terms of charge symmetry violation is very unlikely because of the size of the breaking necessary to fit the data. Of course, the procedure is not entirely consistent because the \(S'_0\) parametrization was constructed with the assumption \(\delta(x) = 0.18\) \(\simeq 0.53\). Eq. (6) should be seen only as a guide.

If we take for instance \(\delta(x) = \overline{\delta}(x)\), we have \(\overline{\delta}(x = 0.18) \simeq 0.19\), which means that the factor giving the breaking is about 55\% of the antiquark distribution itself - clearly too large value. On the other hand, there is no reason at all to interpret the NA51 result solely in terms of isospin breaking between the proton and the neutron. In the general case, the Drell-Yan asymmetry would be:

\[
A_{DY}(x) = \frac{(4\lambda_v(x) - 1)(\lambda_s(x) - 1) + (4\lambda_s(x) - 1)(\lambda_v(x) - 1) - (4\lambda_v(x) + 1)\overline{\delta}(x)/\overline{d}(x) - (1 - 4\lambda_s(x))\delta(x)/d_v(x)}{\{(4\lambda_v(x) + 1)(\lambda_s(x) + 1) + (4\lambda_s(x) + 1)(\lambda_v(x) + 1) + (4\lambda_v(x) + 1)\overline{\delta}(x)/\overline{d}(x) + (1 - 4\lambda_s(x))\delta(x)/d_v(x) + 2(4\lambda_s(x) + 1) + 2(4\lambda_s(x) + 1)(\lambda_s(x) + 1)\overline{d}(x)/d_v(x)\}}. \quad (7)
\]

To write Eq. (7) we made the simplification that, even for broken sea flavour symmetry, the correction \(\overline{\delta}(x)\) from charge symmetry breaking in the sea has the same form for the \(u\) and for the \(d\) quarks. Of course, this does not necessarily need to be the case.

Again, to extract any number from Eq. (7) we need to know the value of the sea and valence quark distributions at a given \(x\). As we include isospin breaking terms, we have the problem that there is no standard quark distribution including these corrections. Moreover, the term involving \(\overline{\delta}(x)\) is potentially important as it is multiplied by a large factor and divided by a small number (viz. \(\overline{d}\)). This is true whether the integral over \(x\) of \(\overline{\delta}(x)\) (and \(\delta(x)\)) is zero or not. This means that to extract \(\lambda_s(x)\) using the measured Drell-Yan asymmetry is at best ambiguous. To estimate the order
of magnitude of $\delta(x)$ and of $\tilde{\delta}(x)$, we will assume that the quark and antiquark distributions are described by the $D'_0$ and $D'_-$ parametrizations. For the $D'_0$ set, the Gottfried sum rule is 0.26 and for the $D'_-$ this value is 0.24, which means that for both sets, $\int_0^1 \tilde{\delta}(x) dx \simeq 0$, but this does not mean that $\tilde{\delta}(x) = 0$ at $x = 0.18$. Using the measured asymmetry and disregarding sea-sea corrections, one gets:

$$\tilde{\delta}(x = 0.18) = 0.169 - 0.053\delta(x = 0.18), \quad \lambda_s \sim 0.88, \quad D'_0$$

$$\tilde{\delta}(x = 0.18) = 0.125 - 0.045\delta(x = 0.18), \quad \lambda_s \sim 0.78, \quad D'_- \quad (8)$$

In fig. 1 we show the behaviour of $\tilde{\delta}(x)$ as a function of $\delta(x)$ for the various parametrizations discussed. A few comments are in place. First, we see that $\tilde{\delta}$ is not strongly dependent on $\delta$ and this dependence becomes weaker as $\lambda_s$ decreases. Moreover, we see that for $\lambda_s = 0.78$, the charge symmetry breaking is of the order 30% ~ 40% of the antiquark distribution. Although this value is high, it is at a specific value of $x$ and we remember that $\lambda_s = 0.78$ is a correction of about 50% to the central value of $\lambda_s = 0.51$ quoted by the NA51 group. We could be less drastic and propose corrections of the order of 20%, bringing the measured central value to $\lambda_s = 0.6$, which is itself a huge correction, providing a sensitive test for any model trying to describe the flavour of the nucleon sea. As a consequence, if we make a linear extrapolation of $\tilde{\delta}(x)$ with $\lambda_s$ as suggested by Fig. 1, this correction of 20% would correspond to a value of $\tilde{\delta}$ around 10% of the antiquark distribution itself. This could well be possible and, from this point of view, the $\lambda_s$ quoted as being experimentally measured only sets a lower limit corresponding to $\tilde{\delta}(x) = \delta(x) = 0$.

We can summarise this letter by saying that, in principle, the discrepancy between theory and experiment found by the NMC could come from flavour symmetry violation in the nucleon sea and charge symmetry breaking in either the the nucleon sea or valence distributions. However, because of the enormous value for $\tilde{\delta}$ needed to fit the experiment with charge symmetry breaking alone, it is more likely that the NMC result implies some strong flavour symmetry breaking in the nucleon sea with a small $\tilde{\delta}$ admixture.

Of course, there are many successful calculations based on pion physics that give a clear indication of an excess of $\tilde{\delta}$ over $\tilde{\pi}$ in the nucleon. On the other hand, the interpretation of the NMC experiment as
a confirmation of broken sea symmetry, does not rule out the possibility that, at a particular $x$, charge symmetry breaking between the neutron and the proton may be at the same level as that of flavour symmetry breaking. Our analysis indicates that it is possible to have $\lambda_s(x)$ larger than the value quoted by the NA51 group at the cost of some charge symmetry breaking between the proton and the neutron at a particular $x$, even if the integrated value of this correction is zero or nearly zero. It is clearly an urgent matter to find experimental ways to separate these two contributions. For now, the important feature to note is that the NA51 result should be seen as a lower limit for $\lambda_s(x)$ and not as an absolute value.

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