Flavor asymmetry of polarized and unpolarized sea quark distributions in the large–$N_c$ limit†

B. Dressler$^a$, K. Goeke$^a$, P.V. Pobylitsa$^{a,b}$, M.V. Polyakov$^{a,b}$, T. Watabe$^{a,c}$, and C. Weiss$^a$

$^a$Institut für Theoretische Physik II, Ruhr-Universität Bochum, D–44780 Bochum, Germany
$^b$Petersburg Nuclear Physics Institute, Gatchina, St.Petersburg 188350, Russia
$^c$RCNP, Osaka University, Mihogaoka 10-1, Ibaraki, Osaka 567-0047, Japan

Abstract

We summarize recent attempts to calculate the flavor asymmetry of the nucleon’s sea quark distributions in the large–$N_c$ limit, where the nucleon can be described as a soliton of an effective chiral theory. We discuss the leading–twist longitudinally polarized and transversity antiquark distributions, $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ and $\delta \bar{u}(x) - \delta \bar{d}(x)$, as well as the unpolarized one, $\bar{u}(x) - \bar{d}(x)$, which appears only in the next–to–leading order of the $1/N_c$–expansion. Results for $\bar{u}(x) - \bar{d}(x)$ are in good agreement with the recent Drell–Yan data from the FNAL E866 experiment. The longitudinally polarized antiquark asymmetry, $\Delta \bar{u}(x) - \Delta \bar{d}(x)$, is found to be larger than the unpolarized one.

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Hard scattering experiments have been a major tool for investigating the structure of the nucleon, giving information about the distribution of quarks, antiquarks and gluons in the nucleon. In the past decade the polarized parton distributions have been the main point of interest. Perhaps even more subtle are the flavor asymmetries of the quark, and, in particular, the antiquark distribution, the experimental study of which has begun only recently.

Flavor asymmetries can in principle be measured in deep-inelastic scattering. The difference of proton and neutron structure functions measured by the NMC Collaboration has allowed to extract information about the first moment of the flavor asymmetry of the unpolarized antiquark distribution in the proton \[1\],

\[
\int_0^1 dx \left[ \bar{u}(x) - \bar{d}(x) \right] = -0.147 \pm 0.039 \quad \text{at} \quad Q = 2 \text{GeV},
\]

showing a large excess of \(d\)- over \(u\)-antiquarks. This circumstance is frequently expressed as a deviation of the so-called Gottfried sum,

\[
I_G = \frac{1}{3} + \frac{2}{3} \int_0^1 dx \left[ \bar{u}(x) - \bar{d}(x) \right],
\]

from the value \(1/3\) (Gottfried sum rule) \[2, 3\]. Note that this sum rule does not follow from any fundamental principles of QCD. A more direct measurement of the antiquark distribution is possible in Drell–Yan production. First limits on the flavor asymmetry of the unpolarized antiquark distribution were obtained by the FNAL-711 experiment \[4\]. The NA51 Collaboration at CERN has measured the ratio \(\bar{d}/\bar{u}\) at a single value of \(x\) \[5\]. Recently, the E866 Experiment at FNAL has for the first time provided direct information about the \(x\)-dependence of the ratio \(\bar{d}/\bar{u}\), and thus about the shape of the unpolarized antiquark asymmetry, over a wide range of \(x\) \[6, 7\].

About the asymmetry of the polarized antiquark distribution little is known at present from experiment. In the parametrizations by Glück et al. of polarized structure function data \(\Delta \bar{u}(x) - \Delta \bar{d}(x)\) was set to zero at the input scale \[8\]. Also, flavor symmetry of the antiquark distribution has been assumed in the extraction of the moments of the polarized valence distribution from the SMC data for semi-inclusive spin asymmetries \[9\]. One may hope that the spin structure experiments planned at CERN (COMPASS \[10\]), HERA and SLAC will provide quantitative information about this asymmetry.

It is clear that the large observed flavor asymmetry of the unpolarized sea quark distribution, Eq.(1), cannot be explained by radiative generation of the antiquark distribution from some input valence quark distribution at a low scale. Attempts of a theoretical explanation of the flavor asymmetry often appeal to the concept of a meson cloud of the nucleon, familiar from nuclear physics \[3, 11\]. For instance, a picture in which the proton state has a component of a virtual \(\pi^+\) and a “core” of neutron quantum numbers, in which the virtual photon can scatter off the pion (Sullivan mechanism \[12\]), could naturally explain the sign and overall magnitude of the observed asymmetry \[3, 11\]. This picture has been extended to include also contributions of the \(\rho\) meson cloud of the nucleon to the asymmetry of the polarized antiquark distribution \[13, 14\]. While intuitively appealing,
it is difficult to maintain a clear distinction between the contributions to the cross section from the “core” and the “cloud” (see also Ref. [15] for a critical discussion).

A more rigorous approach, which nevertheless retains the physical essence of the “meson cloud” picture, is based on the large-$N_c$ limit of QCD. It is well known that in the theoretical limit of a large number of colors QCD becomes equivalent to an effective theory of mesons, in which baryons appear as solitons, i.e., classical solutions characterized by a mean meson field $\langle \Phi \rangle$. At low energies the effective dynamics is described by the chiral Lagrangian for the pion, which appears as a Goldstone boson of the spontaneous breaking of chiral symmetry. The first realization of the idea of the nucleon as a soliton of the pion field by Skyrme [17] was using a particular choice of higher–derivative terms in the chiral Lagrangian. A more realistic effective action, containing all orders in derivatives of the pion field, is defined by the integral over quark fields with a dynamically generated mass, interacting with the pion field in a minimal chirally invariant way [18]. Such an effective action has been derived from the instanton vacuum of QCD, which provides a microscopic mechanism for the dynamical breaking of chiral symmetry [19]. It is valid in a wide range of momenta up to the inverse instanton size, $\bar{\rho}^{-1} = 600$ MeV, which acts as an ultraviolet cutoff. The so–called chiral quark–soliton model of the nucleon based on this effective action [20] has been very successful in describing hadronic observables such as the nucleon mass, $N\Delta$–splitting, electromagnetic and weak form factors etc. [21].

The same approach allows to calculate also the leading–twist parton distributions of the nucleon at a low normalization point ($\mu \sim \bar{\rho}^{-1} = 600$ MeV) [22, 23, 24, 25]. The microscopic derivation of the effective chiral theory from the instanton model of the QCD vacuum allows for a consistent identification of the twist–2 QCD operators with operators in the effective theory [26]. What is important is that the large–$N_c$ description of the nucleon as a chiral soliton is fully field–theoretic and preserves all general properties of the parton distributions, such as positivity and the partonic sum rules which hold in QCD. In particular, it allows for a consistent calculation of the polarized and unpolarized antiquark distributions, and thus of the flavor asymmetry.

The aim of this note is to give an overview of the results of Refs.[22, 23, 24, 25] for the flavor asymmetry of the antiquark distributions. We discuss the unpolarized as well as the longitudinally polarized and transversity antiquark distributions. For details we refer to the original papers.

The large $N_c$–limit implies a number of general statements about the quark and antiquark distributions, which are independent of the specifics of the low–energy dynamics. Quite generally, we aim to describe parton distributions at values of $x$ parametrically of order $x \sim 1/N_c$. On general grounds it can be shown that the twist–2 distribution functions appearing in the leading order of the $1/N_c$–expansion are the flavor–singlet unpolarized and the flavor–nonsinglet longitudinally polarized one ($\Delta q$) [22, 23], as well as
the flavor–nonsinglet transversity distribution ($\delta q$)\(^\text{24}\). They are of the form

$$
\begin{aligned}
&\begin{cases}
u(x) + \bar{d}(x), \quad \bar{u}(x) + d(x) \\
\Delta u(x) - \Delta d(x), \quad \Delta \bar{u}(x) - \Delta \bar{d}(x) \\
\delta u(x) - \delta d(x), \quad \delta \bar{u}(x) - \delta \bar{d}(x)
\end{cases}
\end{aligned}
\right\} = N_c^2 F(N_c x), \quad (3)
$$

where $F(y)$ is a stable function in the large $N_c$–limit, which depends on the particular distribution considered. The respective other flavor combinations appear only in the next–to–leading order of $1/N_c$ and are of the form

$$
\begin{aligned}
&\begin{cases}
u(x) - d(x), \quad \bar{u}(x) - \bar{d}(x) \\
\Delta u(x) + \Delta d(x), \quad \Delta \bar{u}(x) + \Delta \bar{d}(x) \\
\delta u(x) + \delta d(x), \quad \delta \bar{u}(x) + \delta \bar{d}(x)
\end{cases}
\end{aligned}
\right\} = N_c F(N_c x). \quad (4)
$$

Thus, in the $1/N_c$–expansion the polarized flavor asymmetries are parametrically larger than the unpolarized one. Note that this does not necessarily imply that the polarized asymmetries are numerically larger; for this one has to take into account the overall normalization of the distributions (see below).

To actually calculate the (anti–) quark distributions at a low normalization point we need to use the effective low–energy theory. Let us briefly sketch the essential points of this approach (for details see Refs.\(^\text{22, 23}\)). In the effective chiral theory the nucleon is in the large $N_c$–limit characterized by a classical pion field; in the nucleon rest frame it is of “hedgehog” form,

$$
U(x) \equiv e^{i\tau^a n^a(x)} = e^{i\tau^a n^a P(r)}
$$

\(^{(5)}\)

(n\(^a = x^a/|x|, \quad r = |x|), \quad \text{where the profile function, }\) P(r), \quad \text{is determined by minimizing the classical energy. Quarks are described by one–particle wave functions, which are solutions of the Dirac equation in the background pion field,}

$$
\gamma^0 \left(-i\gamma^k \partial_k + M e^{i\gamma^5 \tau^a n^a P(r)}\right) \Phi_n(x) = E_n \Phi_n(x).
$$

\(^{(6)}\)

Here, \(M\) is the dynamical quark mass which arises in the spontaneous breaking of chiral symmetry (numerically, \(M \simeq 350\) MeV \(^\text{19}\)). The spectrum of Eq.(\(6\)) includes a discrete bound–state level as well as a distorted negative and positive Dirac continuum. The discrete level and the negative continuum are occupied, resulting in a state of unity baryon number. Nucleon states with definite spin/isospin quantum numbers are obtained

\(^{1}\text{For the definition of the polarized distributions }\Delta u(x), \Delta d(x)\text{ implied here, see Ref.}\(\text{22, 23}\). \text{We use }\delta u(x), \delta d(x)\text{ to denote }h_{1u}(x), h_{1d}(x)\text{ of Ref.}\(\text{24}\). A general discussion of transversity distributions can be found in Ref.\(\text{27}\).}
after quantizing the rotational zero modes of the classical solution, Eq.(3), which are parametrized by

$$U(x) \rightarrow R(t)U(x)R^\dagger(t),$$

with $R(t)$ an $SU(2)$ rotational matrix. An important point is that the moment of inertia of the soliton is of order $N_c$, hence the angular velocity is small, $\Omega = -iR^\dagger(dR/dt) \sim 1/N_c$.

The basic expressions for the quark and antiquark distributions in this approach have been derived in Refs.[22, 23], starting from the QCD definition of the distribution functions as matrix elements of certain light–ray operators in the nucleon, as well as from their “parton model” definition as the number of particles carrying a given fraction of the nucleon momentum in the infinite–momentum frame; both derivations lead to identical expressions for the distribution functions in the chiral quark–soliton model. The $N_c$–leading distributions, Eq.(3), can be expressed as sums of diagonal matrix elements of quark single–particle operators; e.g. the flavor–nonsinglet polarized quark distribution is given by

$$\Delta u(x) - \Delta d(x) = -\frac{1}{3} (2T_3)N_cM_N \sum_{n \text{ occup.}} \int \frac{d^3k}{(2\pi)^3} \Phi_n^\dagger(k) (1 + \gamma^0\gamma^3) \gamma_5 \tau_3 \delta(k^3 + E_n + xM_N) \Phi_n(k),$$

where $\Phi_n(k)$ are the single particle wave functions, Eq.(6), in momentum representation, and $2T_3 = \pm 1$ for proton and neutron, respectively. Here the sum runs over all occupied quark single–particle levels — the bound state level and the negative continuum. The antiquark distribution is obtained as

$$\Delta \bar{u}(x) - \Delta \bar{d}(x) = -\frac{1}{3} (2T_3)N_cM_N \sum_{n \text{ occup.}} \{x \rightarrow -x\}.$$

Alternatively, it can be expressed as a sum over non-occupied levels (i.e. the positive continuum),

$$\Delta \bar{u}(x) - \Delta \bar{d}(x) = \frac{1}{3} (2T_3)N_cM_N \sum_{n \text{ non-occup.}} \{x \rightarrow -x\}.$$

The completeness of the set of quark single–particle wave functions is essential in ensuring correct properties of the quark and antiquark distributions (sum rules etc.); see Refs.[22, 23] for a detailed discussion. For the chirally–odd transverse polarized distributions the corresponding expressions are Eqs.(8), (9) or (10) with the matrix $\gamma_5$ replaced by $\gamma_5\gamma^1\tau_1$; see Ref.[24].

The flavor–nonsinglet unpolarized quark and antiquark distributions belong to the $N_c$–subleading ones, Eq.(4). In the chiral quark–soliton model this manifests itself in the fact that the expressions for the nucleon matrix elements of the light–cone operator become
non-zero only after expanding to first order in the angular velocity of the soliton; as a result the distributions are given by double sums over quark single–particle levels, similar to the moment of inertia of the classical soliton. We do not quote the lengthy expressions here but rather refer to Ref. [25].

Eqs. (8), (9) or (10) serve as a starting point for a numerical evaluation of the distribution functions. A straightforward way to compute the distributions is to diagonalize the hamiltonian, Eq. (6), and perform the sum over contributions of single–particle levels numerically [23]. Also, it is worthwhile to note that an (almost) analytic answer for the distribution functions can be obtained in the hypothetical limit of large soliton size, which allows one to perform an expansion in the inverse soliton size, analogous to the usual “gradient expansion” for nucleon matrix elements of local operators; see Refs. [22, 23] for details.

The results for the flavor asymmetries of the antiquark distributions are shown in Figs. 1 and 2. The polarized antiquark asymmetries at the low normalization point \( \mu \sim \bar{\rho}^{-1} = 600 \text{ MeV} \), which are leading in the \( 1/N_c \) expansion, are shown in Fig. 1. As can be seen, both the longitudinally polarized as well as the transversity asymmetry have definite sign. The sign of our result is in agreement with the \( \rho \) meson cloud model of Ref. [13] (note that these authors are using a definition of the polarized antiquark distribution with sign opposite to ours); however, the polarized asymmetry obtained in our approach is larger by almost an order of magnitude. It would be extremely interesting to incorporate this asymmetry in analyses of experimental data, e.g. the SMC data for semi-inclusive spin asymmetries [9]. For the first moments of the flavor–nonsinglet antiquark distributions we obtain

\[
\int_0^1 dx \left[ \Delta \bar{u}(x) - \Delta \bar{d}(x) \right] = 0.31, \tag{11}
\]

\[
\int_0^1 dx \left[ \delta \bar{u}(x) - \delta \bar{d}(x) \right] = -0.082. \tag{12}
\]

As already said, these values should be associated with a normalization point of the order \( \mu \sim \bar{\rho}^{-1} = 600 \text{ MeV} \).

We now turn to the unpolarized antiquark asymmetry. The result of the model calculation for \( \bar{u}(x) - \bar{d}(x) \) at the low normalization point \( \bar{\rho}^{-1} = 600 \text{ MeV} \) is shown in Fig. 2. The first moment of the calculated distribution at \( \mu \sim \bar{\rho}^{-1} = 600 \text{ MeV} \) is

\[
\int_0^1 dx \left[ \bar{u}(x) - \bar{d}(x) \right] = -0.17. \tag{13}
\]

Since this quantity exhibits only very weak scale dependence it is justified to compare this directly with the NMC value at \( Q = 2 \text{ GeV} \), Eq. (1). We see that our value is consistent

\(^2\)In Fig. 1 we quote results obtained with the variational (arctan–) soliton profile of Refs. [22, 23], using the “interpolation formula” and a Pauli–Villars ultraviolet cutoff applied to the Dirac continuum contribution. The contribution of the discrete level is not regularized.

\(^3\)A calculation of this distribution in a related approach has been reported in Ref. [28]; see Ref. [25] for a discussion of differences.
with the NMC result. We note that the E866 Drell–Yan data for \( \bar{d}(x)/\bar{u}(x) \) [6], combined with the CTEQ4M parametrization of \( \bar{u}(x) + \bar{d}(x) \) [29], suggest a value for the integral Eq.(1) of about 2/3 the NMC result, which, however, depends on the parametrization of the parton distributions used to estimate the contributions from the unmeasured region \( x < 0.02 \); see Ref.[7] for a detailed discussion of the compatibility of this result with the NMC measurement. Note also that there are systematic uncertainties in our model calculation related to the use of the \( 1/N_c \)–expansion as well as the lack of knowledge of the precise form of the ultraviolet cutoff of the effective chiral theory [22, 23].

The first moment of the flavor asymmetry of the unpolarized antiquark distribution (the Gottfried sum) has been studied previously in the Skyrme model [30] and the chiral quark–soliton model [31]. These calculations attempted to calculate the Gottfried sum directly, using certain operator expressions for this quantity which were not derived from a consistent identification of the parton distribution functions in the low–energy model.

For the \( x \)–dependence of the unpolarized antiquark asymmetry data are available from the Fermilab E866 Drell–Yan experiment [6]. We cannot directly compare the measured ratio \( \bar{d}(x)/\bar{u}(x) \) to the model calculation, since this quantity is inhomogeneous in the parameter \( 1/N_c \), and to compute it we would need to know the flavor–singlet distribution, \( \bar{u}(x) + \bar{d}(x) \), in next–to–leading order of the \( 1/N_c \)–expansion, cf. Eqs.(3) and (4). We therefore compare \( \bar{u}(x) - \bar{d}(x) \), which was extracted from the E866 data for \( \bar{d}(x)/\bar{u}(x) \) combined with the CTEQ4M parametrization of \( \bar{u}(x) + \bar{d}(x) \). Fig. shows the data for \( \bar{d}(x) - \bar{u}(x) \) extracted from the analysis of Ref.[7], together with the result of the calculation in the chiral quark–soliton model of Ref.[25]. Here we have evolved the distribution calculated in Ref.[25] from the low normalization point (\( \mu \sim 600 \text{MeV} \)) to the scale of \( Q = 7.35 \text{GeV} \), using leading–order evolution with \( \Lambda_{\text{QCD}} = 232 \text{MeV} \) for \( N_f = 3 \). We remark that the results of the present model are not meaningful for small \( x \), since for values of \( x \) parametrically of the order \( (M\bar{\rho})^2/N_c (\bar{\rho}^{-1} \text{is the inverse average instanton size, cf. above}) \) effects not taken into account in the present calculation become important; see [32, 25] for details.

Of interest is also the comparison of the integral of this distribution over the measured \( x \)–region, \( 0.02 < x < 0.345 \), with the result of the model calculation. After evolution of the calculated antiquark distribution we find

\[
\int_{0.02}^{0.345} dx \left[ \bar{u}(x) - \bar{d}(x) \right] = -0.108 \quad \text{at} \quad Q = 7.35 \text{GeV}, \quad (14)
\]

to be compared with the value \(-0.068 \pm 0.007\text{(stat.)} \pm 0.008\text{(syst.)}\) obtained in the analysis of Ref.[7] (see that paper for details). For the first moment we obtain

\[
\int_{0.02}^{0.345} dx \ x \left[ \bar{u}(x) - \bar{d}(x) \right] = -0.0096 \quad \text{at} \quad Q = 7.35 \text{GeV}, \quad (15)
\]

to be compared with \(-0.0065 \pm 0.0010 \) [6].

To summarize, we have shown that the large–\( N_c \) picture of the nucleon as a chiral soliton naturally gives a flavor asymmetry of the unpolarized antiquark distribution in agreement with the observed violation of the Gottfried sum rule, and with the recent first results for the \( x \)–dependence of the asymmetry from Drell–Yan production. Equally important, this picture predicts a sizable asymmetry of the polarized antiquark distribution.
(both longitudinally polarized and transversity distribution). It would be extremely interesting to incorporate this information in new parametrizations of the parton distribution functions, or directly in the analyses of experimental data.

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Figure 1: The calculated flavor asymmetry of the longitudinally polarized antiquark distribution in the proton, $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ (solid line), and the transversity antiquark distribution, $\delta \bar{d}(x) - \delta \bar{u}(x)$ (dashed line), at the low normalization point.
Figure 2: The calculated unpolarized antiquark asymmetry in the proton, $\bar{d}(x) - \bar{u}(x)$, at the low normalization point [25].
Figure 3: The values for $\bar{d}(x) - \bar{u}(x)$ in the proton at $Q = 7.35$ GeV from the analysis of the FNAL E866 data of Ref. [7], compared to the distribution calculated in Ref. [24], evolved from $\mu = 600$ MeV to the experimental scale (dashed line).