Polarized antiquark flavor asymmetry: 
Pauli blocking vs. the pion cloud

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The flavor asymmetry of the unpolarized antiquark distributions in the proton, \( \bar{d}(x) - \bar{u}(x) > 0 \), can qualitatively be explained either by Pauli blocking by the valence quarks, or as an effect of the pion cloud of the nucleon. In contrast, predictions for the polarized asymmetry \( \Delta \bar{u}(x) - \Delta \bar{d}(x) \) based on \( \rho \) meson contributions disagree even in sign with the Pauli blocking picture. We show that in the meson picture a large positive \( \Delta \bar{u}(x) - \Delta \bar{d}(x) \) is obtained from \( \pi N - \sigma N \) interference–type contributions, as suggested by chiral symmetry. This effect restores the equivalence of the “quark” and “meson” descriptions also in the polarized case.

That the low–energy structure of the nucleon can be described equally well in terms of quark or meson degrees of freedom has been one of the fundamental beliefs of modern hadronic physics. While often one description is far more efficient than the other, there is a basic conviction that both should give equivalent results when carried on to higher accuracy, which, unfortunately, often turns out to be impossible in practice.

Particularly interesting properties in this respect are the parton (quark– and antiquark) distributions in the nucleon. Although measured in deep–inelastic scattering at large momentum transfers, these are low–energy characteristics of the nucleon, whose origin can be understood on grounds of the same effective dynamics which give rise to the hadronic characteristics of the nucleon such as form factors, magnetic moments, etc.

It is now well established that the antiquark distributions in the proton are not flavor symmetric: \( \bar{d}(x) > \bar{u}(x) \). Deep–inelastic lepton scattering has convincingly demonstrated the violation of the so–called Gottfried sum rule \( \bar{d}(x) = \bar{u}(x) \), and the E866 Drell–Yan pair production data \( 1, 2 \) as well as the HERMES results on semi-inclusive deep–inelastic scattering \( 3, 4 \) allow to map even the \( x \)–dependence of the asymmetry. The origin of this asymmetry can qualitatively be explained in either a quark or a meson picture. In the quark picture it can be attributed to the “Pauli blocking” effect \( 1, 2, 3 \). For instance, in the bag model, where the valence quarks are bound by a scalar field, the Dirac vacuum inside the proton differs from the free one, corresponding to the presence of a non–perturbative “sea” of quark–antiquark pairs. Since the wave function of a localized valence quark in the proton rest frame has components corresponding to antiquarks in the infinite–momentum frame, the valence quarks “block” quark–antiquark pairs of the same flavor, leading to an excess of \( \bar{d}(x) \) over \( \bar{u}(x) \) \( 1, 2 \). The mesonic picture attributes the antiquark flavor asymmetry to the contribution of the “pion cloud” of the proton to deep–inelastic scattering (Sullivan mechanism) \( 4, 5 \). The asymmetry arises because fluctuations \( p \to n \pi^+ \) are more likely than \( p \to \Delta^+ \pi^- \) due to the larger mass of the \( \Delta \) resonance, which implies a larger number of \( \pi^+ \) than \( \pi^- \) in the proton’s cloud. It needs to be stressed that both explanations are of qualitative nature; the difficulties encountered when trying to turn them into serious dynamical models have been discussed in the literature, see e.g. Refs. \( 6 \). Nevertheless, the fact that the two pictures give compatible results for the sign and order–of–magnitude of \( \bar{d}(x) - \bar{u}(x) \) has been registered as a remarkable instance of equivalence of a quark and a meson description.

Recently the polarized antiquark flavor asymmetry, \( \Delta \bar{u}(x) - \Delta \bar{d}(x) \), has become a focus of attention. It is expected that this asymmetry will be measured with good accuracy in polarized semi–inclusive particle production at the HERMES experiment, and, in particular, in future polarized Drell–Yan pair or \( W^\pm \) production experiments at RHIC \( 7, 8, 9, 10 \). The published semi-inclusive data from HERMES \( 11 \) and SMC \( 12 \) do not yet allow for significant conclusions \( 13 \); improved data from HERMES are expected to be released soon. On the theoretical side, interest was caused by an estimate within the chiral quark–soliton model of the nucleon, based on the large–\( N_c \) limit of QCD, which suggests a surprisingly large positive \( \Delta \bar{u}(x) - \Delta \bar{d}(x) \), larger than the unpolarized asymmetry, \( \bar{d}(x) - \bar{u}(x) \) \( 14 \).

It is natural to ask what the two standard explanations for the unpolarized asymmetry predict for the polarized case. The Pauli blocking picture implies that valence quarks “block” antiquarks of the same flavor but with opposite spin, which would give \( \Delta \bar{u}(x) - \Delta \bar{d}(x) > 0 \) \( 1, 2 \). Glick and Reya \( 15 \) have suggested a phenomenological parametrization based on the ansatz \( \Delta \bar{u}(x)/\Delta \bar{d}(x) = \Delta \bar{d}(x)/\Delta \bar{u}(x) \), which qualitatively expresses this idea. The resulting asymmetry at a scale of \( \mu^2 = 1 \text{ GeV}^2 \), as obtained with the AAC parametrization \( 16 \) of the polarized valence and flavor–singlet sea quark distributions, is shown in Fig. \( 6 \) (dotted line). It should be stressed, however, that the simple Pauli blocking argument can predict neither the magnitude nor the \( x \)–dependence of the polarized asymmetry. Nevertheless, it is natural to assume that in such a picture the polarized asymmetry...
should be of the same order of magnitude as the unpolarized one

In the meson cloud picture, the $\pi N$ contribution (Sul-

The inclusion of $\rho N$ contributions leads to a non-zero

The matrix element of the twist–2 axial vector light–ray

tion of a model is assumed to be valid. On general grounds the

and $\bar{u}$ problem of the dynamical nature of the

graph denotes the “bosonized” version of the isovector

tion to the matrix element from the “interference type”

intermediate–range

the chiral partner of the pion, and which mediates the

contributions was first pointed out in Ref.\[17\]. Here

nucleon parton distributions. The possibility of such

a sizable positive $\Delta \bar{u}$–

larized antiquark flavor asymmetry is by no means a nec-

ized asymmetry, fails in the polarized case.

Thus wonder whether the equivalence of the quark and

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Here $0 < x < 1$, and $z^\pm = (z^0 \pm z^3)/\sqrt{2}$ and $z_\perp$ are the usual light–like coordinates, $\tau^3$ the isospin Pauli matrix, and $\bar{U}, U$ the proton spinors. We consider the contribution to the matrix element from the “interference type” graphs of Fig. 1. The blob in the upper parts of the graphs denotes the “bosonized” version of the isovector axial vector twist–2 operator, i.e., the operator expressed in terms of the $\pi$ and $\sigma$ fields of our effective low–energy model. We suppose here that the QCD operator is normalized at a scale of $\sim 1$ GeV, up to which the effective model is assumed to be valid. On general grounds the

music of the QCD operator to an operator in the effective model must be of the form

$$\langle \gamma \, g_{\pi}\psi(-z/2)\gamma^\tau_5\sigma^a\psi(z/2)\rangle_{z\rightarrow0}$$

up to terms of higher orders in derivatives of the fields, which we shall neglect. Here $g_{\pi\sigma}(y)$ is a scalar function, which we refer to as the $\pi–\sigma$ transition parton density$^\tau$. The expansion of Eq.(3) in powers of the light–like distance, $z$, implies that the local twist–2 spin–$n$ operator is mapped onto the local twist–2 spin–$n$ operator built from the $\pi$ and $\sigma$ fields, with the coefficient given by the $n$th moment of $g_{\pi\sigma}$. Time reversal invariance requires $g_{\pi\sigma}(y) = g_{\pi\sigma}(-y)$. The normalization of the function follows from considering the limit $z \rightarrow 0$, in which the R.H.S. of Eq.(3) must reduce to the isovector axial current operator in the $\pi$ and $\sigma$ fields, $\sigma(0) \partial^\tau_x \pi^a(0)$, whose form is completely determined by chiral symmetry. This requires

$$\int_{-1}^{1} dx \, g_{\pi\sigma}(y) = 2.$$  \hspace{1cm} (3)$$

In order to constrain the $y$–dependence of $g_{\pi\sigma}$ we note that a global chiral rotation transforms the axial vector operators of Eq.(3) into the corresponding vector operators, whose matrix element between pion states defines the valence quark distribution in the pion, $v_\pi(y)$. Thus, in our approximation we can identify

$$g_{\pi\sigma}(y) = \frac{1}{2}v_\pi(|y|).$$  \hspace{1cm} (4)$$

In our estimate we use the parametrization of Ref.[29] for $v_\pi(y)$, obtained from fitting $\pi N$ Drell–Yan data.

The contribution of the two graphs of Fig. 1 to the polarized flavor asymmetry can be put in the form

$$\Delta \bar{u}(x) - \Delta \bar{d}(x) = \int_{x}^{1} \frac{dy}{y} \, g_{\pi\sigma}(y) \, W_{z\sigma}(\frac{x}{y}).$$  \hspace{1cm} (5)$$

FIG. 1: $\pi N–\sigma N$ “interference type” graphs contributing to $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ in the proton. The crosses denote the positions of the quark fields in the QCD twist–2 operator, $z/2$ and $-z/2$, cf. Eq.(3).
where \( W_{\pi\sigma}(x/y) \) denotes the correlation function of the \( \pi- \) and \( \sigma\)-fields in the nucleon depending on the + component of the fields’ momenta \((v \equiv x/y)\)

\[
W_{\pi\sigma}(v) = \frac{g_{\pi NN} g_{NN}}{4\pi} \int \frac{d^3k_\perp}{(2\pi)^2} \times \frac{x[\mathbf{k}_\perp^2 + v(2-v)M_N^2]}{[\mathbf{k}_\perp^2 + v^2M_N^2 + (1-v)M^2_\sigma]} \times \frac{1}{[\mathbf{k}_\perp^2 + v^2M_N^2 + (1-v)M^2_\sigma]}.
\]

This function plays a role analogous to the “number of pions with momentum fraction \( v \)” in the usual \( \pi N \) contribution to the unpolarized asymmetry [8]. The integral over the transverse momentum \( \mathbf{k}_\perp \) contains a would-be logarithmic divergence which is regularized by cutoffs associated with the \( \pi N \) and \( \sigma N \) vertices, not indicated in Eq. (6). For a numerical estimate we use coupling constants \( g_{\pi NN} = 13.5, g_{NN} = 14.6, M_\pi = 0.72 \text{ GeV}, \) and exponential cutoffs with \( \Lambda_\pi = 1.1 \text{ GeV} \) and \( \Lambda_\sigma = 1.6 \text{ GeV} \) [24]. The result for \( \Delta \bar{u}(x) - \Delta \bar{d}(x) \) is shown by the solid line in Fig. 2. The dashed line in the same figure shows the \( \pi N \) contribution to the unpolarized asymmetry, \( \bar{d}(x) - \bar{u}(x) \), evaluated with the same parameters. One sees that the polarized asymmetry incurred from \( \pi N - \sigma N \) interference is positive, and of the same order of magnitude as the unpolarized one. (In Fig. 2, for the sake of comparison, we show \( \bar{d}(x) - \bar{u}(x) \) as generated by \( \pi N \) contributions only; it is known that the inclusion of intermediate \( \Delta \) states reduces this value by almost 50% [8].)

In Fig. 3 we compare the \( \pi N - \sigma N \) interference contribution to \( \Delta \bar{u}(x) - \Delta \bar{d}(x) \) (solid line) with the asymmetry obtained with the phenomenological Pauli–blocking ansatz of Ref. [21]. One sees that both suggest a sizable positive flavor asymmetry \( \Delta \bar{u}(x) - \Delta \bar{d}(x) \). In this sense, one may say that the same qualitative equivalence of the “quark” and “meson” descriptions holds as in the case of unpolarized asymmetry, \( \bar{d}(x) - \bar{u}(x) \).

We stress that our point here is entirely qualitative, concerning only the sign and order–of–magnitude of the asymmetry. Neither the Pauli–blocking ansatz of Ref. [21] nor the \( \pi N - \sigma N \) contribution in the meson cloud model can claim to give a quantitative description of the \( x \)-dependence of the asymmetry. (We also refrain from quoting any error estimate for the meson cloud model.) Nevertheless, given the disagreement even in sign of the previous \( \rho \) meson cloud estimates with the Pauli blocking picture we feel that the agreement at the present level is remarkable. Note also that in the near future experiments will be able to determine little more but the sign and order–of–magnitude of \( \Delta \bar{u}(x) - \Delta \bar{d}(x) \).

FIG. 2: Various contributions to the antiquark flavor asymmetry in the proton (unpolarized and polarized) in the meson cloud model (scale \( \mu^2 = 1 \text{ GeV}^2 \)). Dashed line: \( x\bar{d}(x) - \bar{u}(x) \), \( \pi N \) contributions (Sullivan mechanism). Dotted line: \( x[\Delta \bar{u}(x) - \Delta \bar{d}(x)] \), \( \rho N \) contribution [22]. Solid line: \( x[\Delta \bar{u}(x) - \Delta \bar{d}(x)] \), \( \pi N - \sigma N \) interference contribution.

FIG. 3: Comparison of model results for the polarized flavor asymmetry \( x[\Delta \bar{u}(x) - \Delta \bar{d}(x)] \) in the proton (\( \mu^2 = 1 \text{ GeV}^2 \)). Dotted line: Pauli blocking ansatz of Ref. [21]. Dashed line: Chiral quark–soliton model [18]. Solid line: \( \pi N - \sigma N \) interference contribution in the meson cloud model (cf. Fig. 2).

Also in Fig. 3, we compare the estimates from the \( \pi N - \sigma N \) contribution in the meson cloud model and the Pauli blocking ansatz of Ref. [21] with the result of the chiral quark–soliton model (ChQSM), which was the first to predict a large positive flavor asymmetry \( \Delta \bar{u}(x) - \Delta \bar{d}(x) \) [18]. This comparison is interesting also from a conceptual point of view. In the ChQSM, motivated by the large–\( N_c \) limit of QCD [27], the nucleon is described by a classical pion field, in which quarks move in single–particle orbits. The quark spectrum includes a bound–state level in addition to the polarized negative and positive Dirac continua [25]. In a sense, this model contains the physical essence of both the “Pauli blocking” and the “meson cloud” picture, uniting both of them in a
consistent framework. The contribution of the bound–state level of quarks to $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ is positive, in agreement with the “Pauli blocking” argument. The contribution to $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ from the Dirac sea of quarks can be computed approximately in an expansion in gradients of the classical pion field polarizing the vacuum; the result is given as a spatial integral of the the isovector–pseudoscalar and scalar–isoscalar combinations of the classical field, reminiscent in quantum numbers of $\pi N$ and $\sigma N$ interference contributions in the meson cloud model [7]. Thus, the semiclassical description of the nucleon at large $N_c$ reproduces the physics of “meson cloud” contributions to the nucleon parton distributions without appealing to the notion of individual meson exchange graphs. In this way it avoids the conceptual problems of the meson cloud model related to the neglect of multiple exchanges and the large virtuality of the exchanged mesons (see Ref. [10] for a critical discussion).

To summarize, we have argued that the “Pauli blocking” and the “meson cloud” scenario are both consistent with a positive polarized antiquark flavor asymmetry, $\Delta \bar{u}(x) - \Delta \bar{d}(x)$, of comparable magnitude as the unpolarized one, $\bar{d}(x) - \bar{u}(x)$. The key to this equivalence has been the inclusion of $\pi N - \sigma N$ “interference type” contributions in the meson cloud picture, whose importance is suggested by chiral symmetry. Our qualitative arguments explain the large value of $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ predicted by the chiral quark–soliton model. This should be good news for experiments aimed at extracting $\Delta \bar{u}(x) - \Delta \bar{d}(x)$, both from semi-inclusive deep-inelastic scattering and Drell–Yan / $W^\pm$ production.

We are grateful to M. V. Polyakov for many helpful suggestions, and to A. W. Thomas and W. Melnitchouk for useful discussions. R. J. F. is supported by the Alexander von Humboldt Foundation (Feodor Lynen Fellowship), C. W. by DFG (Heisenberg Fellowship). This work has been supported by DFG and BMBF.

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