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Short Note

Polarized antiquark flavor asymmetry $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ and the pion cloud

R.J. Fries[1,2], A. Schäfer[1], and C. Weiss[1,a]

[1] Institut für Theoretische Physik, Universität Regensburg, D-93053 Regensburg, Germany
[2] Physics Department, Duke University, P.O. Box 90305, Durham, NC 27708, USA

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Abstract. The flavor asymmetry of the unpolarized antiquark distributions in the proton, $\bar{u}(x) - \bar{d}(x) < 0$, can qualitatively be explained as an effect of the pion cloud. Corresponding predictions have been made for the polarized asymmetry, $\Delta\bar{u}(x) - \Delta\bar{d}(x)$, based on rho-meson contributions. These estimates differ in sign and magnitude from those obtained in quark-based models, which give $\Delta\bar{u}(x) - \Delta\bar{d}(x) > 0$. Using a simple chiral linear sigma model as an example, we demonstrate that in the meson cloud picture a large positive $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ can be obtained from π-σ interference contributions. This calls into question previous estimates based on rho-meson contributions alone, and indicates how the results of the meson cloud picture may be reconciled with those of quark-based models.

PACS. 12.39.Fe Chiral Lagrangians – 13.60.Hb Total and inclusive cross-sections (including deep-inelastic processes) – 13.88.+e Polarization in interactions and scattering

The flavor asymmetries of the nucleon's antiquark distributions have attracted considerable interest in recent years. 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 gives rise to hadronic characteristics such as form factors, magnetic moments, etc. It is now well established that the unpolarized 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 [1], and the E866 Drell-Yan pair production data [2] as well as the HERMES results on semi-inclusive deep-inelastic scattering [3] allow to map even the x-dependence of the asymmetry. Various theoretical explanations for the origin of this asymmetry have been offered [1]. In particular, it has been argued that it can be explained as an effect of the "pion cloud" of the proton on the parton distributions (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 Δ-resonance, which implies a larger number of π^+ than π^- in the proton's cloud. It should be noted that a quantitative description of the observed asymmetry based on pion cloud contributions alone requires large pion virtualities, for which the very notion of pion exchange becomes questionable; see, *e.g.*, ref. [6] for a discussion. Nevertheless, this simple picture has attracted considerable interest.

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 [7–10]. 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]. Similar results have been obtained in

[a] e-mail: christian.weiss@physik.uni-regensburg.de

other quark-based models, such as the bag model [15] and the statistical models of parton distributions of refs. [16] and [17].

There have also been attempts to understand the polarized asymmetry on the basis of meson cloud contributions, in analogy to the Sullivan mechanism for the unpolarized asymmetry. The πN and $\pi\Delta$ configurations, which "work" in the unpolarized case, give zero contribution to the polarized flavor asymmetry. This has lead people to consider also vector mesons in this picture. The inclusion of ρN contributions [18] indeed leads to a non-zero $\Delta\bar{u}(x) - \Delta\bar{d}(x)$, which, however, is an order of magnitude smaller than the unpolarized asymmetry, and has opposite sign compared to the results of the quark-based models [15–17] and the chiral quark-soliton model [14]. Reference [19] studied ρN-πN interference contributions relevant at small x, see also ref. [15], the sign again opposite to the results of quark-based models. The estimate of ref. [18] was refined by including also higher-twist components of the ρ-meson structure function [20], which, however, do not change the order of magnitude of the result. This apparent disagreement between the "mesonic" and the "quark-based" descriptions of the polarized asymmetry has left the impression that the situation with theoretical predictions of the polarized asymmetry was essentially unclear.

Here, we want to argue that a negative $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ is by no means a necessary consequence of the meson cloud picture. A sizable positive asymmetry is naturally obtained from the interference of πN and "σN" components of the nucleon wave function. By this we mean a scalar-isoscalar exchange, which, *e.g.*, mediates the intermediate-range NN interaction in the meson exchange parametrization of ref. [21] (Bonn potential). The possibility of such contributions to the polarized asymmetry was first pointed out in ref. [13]. The problem of the dynamical nature of the "σ-meson" —whether it should be regarded as an effective description of a $\pi\pi$ resonance— has been discussed extensively in the literature and shall not be our main concern here. Rather, we want to make two qualitative points. First, the large asymmetry obtained from πN-"σN" interference calls into question previous calculations within the meson cloud model which did not include this effect in one form or another [18–20]. Second, including πN-"σN" interference in the meson cloud picture, one can restore qualitative agreement with the quark-based predictions for the polarized asymmetry.

To illustrate our points, we compute the πN-σN interference contributions to $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ in the proton in a version of the meson cloud model with elementary π and σ fields coupled to the nucleon (linear sigma model). This effective model incorporates the spontaneous breaking of chiral symmetry. The sigma-meson appears as the chiral partner of the pion; its mass is due to the spontaneous breaking of chiral symmetry.

The isovector polarized quark and antiquark distributions in the proton are defined by the matrix element of the twist-2 axial vector QCD light-ray operator ($\bar\psi$ and ψ are the QCD quark fields):

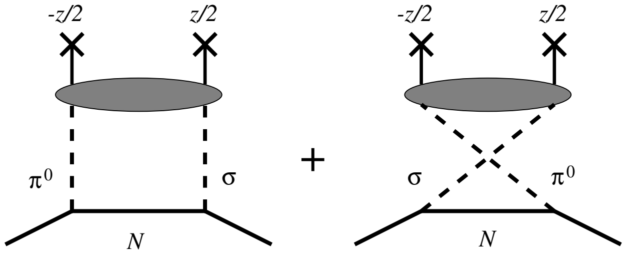

Fig. 1. πN-σN "interference-type" graphs contributing to $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ in the proton. The crosses denote the quark fields in the QCD twist-2 operator, cf. eq. (1).

$$\int \frac{\mathrm{d}z^-}{2\pi} e^{\pm ixp^+z^-} \langle p|\bar\psi(-z/2)\gamma^+\gamma_5\tau^3\psi(z/2)|p\rangle_{z^+,\mathbf{z}_\perp=0} = \bar{U}\gamma^+\gamma_5 U \times \left\{ \begin{array}{l} [\Delta u(x) - \Delta d(x)] \\ [\Delta\bar{u}(x) - \Delta\bar{d}(x)] \end{array} \right. . \qquad (1)$$

Here, $0 < x < 1$, and $z^\pm = (z^0 \pm z^3)/\sqrt{2}$ and $\mathbf{z}_\perp$ are the usual light-like coordinates, τ^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 vertices in the lower parts of the graphs are the standard pseudoscalar-isovector πN and scalar-isoscalar σN coupling. The blob in the upper parts denotes the "bosonized" version of the isovector axial vector twist-2 operator, *i.e.*, the operator expressed in terms of the π and σ fields of our effective low-energy model. We suppose here that the QCD operator is normalized at a scale of $\sim 1\,\mathrm{GeV}$, up to which the effective model is assumed to be valid. On general grounds the matching of the QCD operator with an operator in the effective model must be of the form

$$\bar\psi(-z/2)\gamma^+\gamma_5\tau^a\psi(z/2)|_{z^2=0} \to \int_{-1}^{1} \mathrm{d}y\, g_{\pi\sigma}(y)\, \sigma(-yz/2)\, \overleftrightarrow{\partial}^+ \pi^a(yz/2)|_{z^2=0}\ , \qquad (2)$$

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 "π-σ transition parton density". The expansion of eq. (2) 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 π and σ 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 $z \to 0$. The RHS of eq. (2) must reduce to the isovector axial current operator in the π and σ fields, $\sigma(0)\, \overleftrightarrow{\partial}^\mu \pi^a(0)$, whose form is completely determined by chiral symmetry. This implies

$$\int_{-1}^{1} \mathrm{d}x\, g_{\pi\sigma}(y) = 2\ . \qquad (3)$$

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. (2) 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

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

In our estimate we use the parametrization of ref. [22] for $v_\pi(y)$, obtained from fitting πN Drell-Yan data.

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

$$\Delta\bar{u}(x) - \Delta\bar{d}(x) = \int_x^1 \frac{\mathrm{d}y}{y}\; g_{\pi\sigma}(y)\; W_{\pi\sigma}\left(\frac{x}{y}\right) , \tag{5}$$

where $W_{\pi\sigma}(x/y)$ denotes the correlation function of the π and σ fields in the nucleon depending on the + component of the fields' momenta ($v \equiv x/y$):

$$W_{\pi\sigma}(v) = \frac{g_{\pi NN} g_{\sigma NN}}{4\pi} \int \frac{\mathrm{d}^2 k_\perp}{(2\pi)^2} \times \frac{v[\mathbf{k}_\perp^2 + v(2-v)M_N^2]}{[\mathbf{k}_\perp^2 + v^2 M_N^2 + (1-v)M_\pi^2]} \times \frac{1}{[\mathbf{k}_\perp^2 + v^2 M_N^2 + (1-v)M_\sigma^2]} \; . \tag{6}$$

This function plays a role analogous to the "number of pions with momentum fraction v" in the usual πN contribution to the unpolarized asymmetry [5]. The integral over the transverse momentum $\mathbf{k}_\perp$ contains a would-be logarithmic divergence which is regularized by cutoffs associated with the πN and σN vertices, not indicated in eq. (6). For a numerical estimate we use coupling constants $g_{\pi NN} = 13.5$, $g_{\sigma NN} = 14.6$, $M_\sigma = 0.72\,\mathrm{GeV}$ [21], and exponential cutoffs with $\Lambda_\pi = 1.1\,\mathrm{GeV}$ and $\Lambda_\sigma = 1.6\,\mathrm{GeV}$; the relation between the parameters for different functional forms of the cutoff is discussed, *e.g.*, in the articles by Kumano quoted in ref. [5], and in ref. [6]. The result for $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ is shown in fig. 2 (solid line). The dashed line shows the πN contribution to the unpolarized asymmetry, $\bar{d}(x) - \bar{u}(x)$, evaluated with the same parameters. One sees that the polarized asymmetry incurred from πN-σN 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 πN contributions only; it is known that the inclusion of intermediate Δ states reduces this value by almost 50% [5]. In principle Δ contributions could be included also in the estimate of the polarized asymmetry; however, we would not expect them to change the sign and order of magnitude of the results. Finally, the dotted line in fig. 2 shows the polarized asymmetry obtained from ρN contributions [18].

In fig. 3 we compare the πN-σN interference contribution to $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ (solid line) with the result obtained in the chiral quark-soliton model (dashed line). Also shown is the phenomenological Pauli-blocking–inspired parametrization of ref. [23] (dotted line). All approaches suggest a sizable positive $\Delta\bar{u}(x) - \Delta\bar{d}(x)$. Similar qualitative agreement would be observed with the bag model result of ref. [15] and the statistical quark models of refs. [16,17]. We stress that our point here is entirely qualitative, concerning only the sign and order of magnitude of the asymmetry. We are not suggesting that the πN-σN contributions in our simple chiral model can claim to give a quantitative description of the magnitude of the asymmetry and its x-dependence. Nevertheless, given the disagreement even in sign of the previous ρ-meson cloud estimates with the quark-based models, we think that the agreement at the present level is worth noting. To the very least, our results indicate that the ρN contributions are not the dominant ones in a hadronic description of the polarized asymmetries.

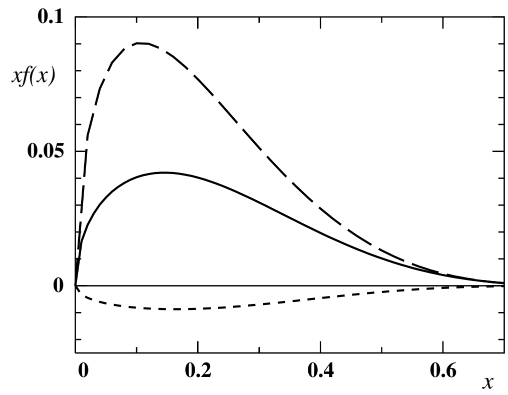

Fig. 2. Various contributions to the antiquark flavor asymmetry in the proton (unpolarized and polarized) in the meson cloud model (scale $\mu^2 = 1\,\mathrm{GeV}^2$). Dashed line: $x[\bar{d}(x) - \bar{u}(x)]$, πN contributions (Sullivan mechanism). Dotted line: $x[\Delta\bar{u}(x) - \Delta\bar{d}(x)]$, ρN contribution [18]. Solid line: $x[\Delta\bar{u}(x) - \Delta\bar{d}(x)]$, πN-σN interference contribution.

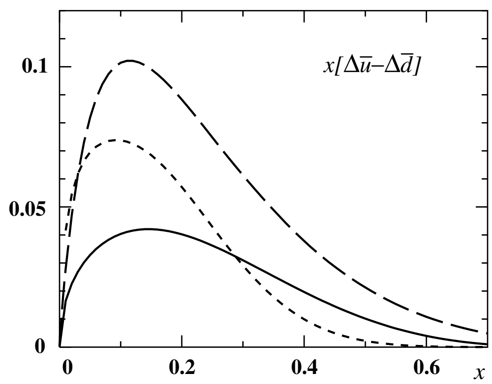

Fig. 3. Comparison of model results for the polarized flavor asymmetry $x[\Delta\bar{u}(x) - \Delta\bar{d}(x)]$ in the proton ($\mu^2 = 1\,\mathrm{GeV}^2$). Dotted line: Pauli-blocking ansatz of ref. [23]. Dashed line: Chiral quark-soliton model [14]. Solid line: πN-σN interference contribution in the meson cloud model (cf. fig. 2).

A consistent and quantitative description of the polarized antiquark flavor asymmetry is provided by the chiral quark-soliton model of the nucleon, based on the large-N_c limit of QCD [14]. In this approach the nucleon is described as a self-consistent configuration characterized by a classical pion field, in which quarks move in single-particle orbits. The quark spectrum includes a discrete bound-state level in addition to the polarized Dirac sea [24]. The quark/antiquark distributions are computed by summing over the contributions of all quark levels, including both the bound-state level and the polarized Dirac sea. The result for $\Delta\bar{u}(x)-\Delta\bar{d}(x)$ is shown in fig. 3 (dashed line). Moreover, as was shown in refs. [14,13], in this model the polarized flavor asymmetry can be computed analytically by way of an expansion in gradients of the classical pion field characterizing the nucleon. The resulting expression for $\Delta\bar{u}(x)-\Delta\bar{d}(x)$ has the form of a spatial integral of the the isovector-pseudoscalar and scalar-isoscalar combinations of the classical pion field, reminiscent in quantum numbers of the πN-σN interference contribution in the meson cloud model [13]. Thus, the semi-classical 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. [6] for a critical discussion).

To summarize, we have shown that the inclusion of πN-σN interference contributions in a meson cloud picture naturally leads to a large positive polarized antiquark flavor asymmetry $\Delta\bar{u}(x) - \Delta\bar{d}(x)$. This indicates that the results of previous meson cloud estimates based on ρ-meson contributions alone may be misleading [18–20]. With πN-σN interference contributions included, the meson cloud estimate for $\Delta\bar{u}(x)-\Delta\bar{d}(x)$ is of the same sign and order of magnitude as the asymmetry predicted by the chiral quark-soliton model, as well as other quark-based models. 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.

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