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The $\bar{d}-\bar{u}$ asymmetry of the proton in a Pion Cloud Model approach

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Abstract

We study the $\bar{d}-\bar{u}$ asymmetry of the proton in a model approach in which hadronic fluctuations of the nucleon are generated through gluon splitting and recombination mechanisms. Within this framework, it is shown that the $\bar{d}-\bar{u}$ asymmetry of the proton is consistently described by including only nucleon fluctuations to $|\pi N\rangle$ and $|\pi\Delta\rangle$ bound states. Predictions of the model closely agree with the recent experimental data of the E866/NuSea Collaboration.

Key-Words: Nucleons, flavor asymmetries, sum rules, quark models, pion cloud, non-perturbative QCD

Pacs No: 14.20Dh, 14.65Bt,11.30Hv, 12.39~x

Recently, the E866/NuSea Collaboration has measured a noticeable $\bar{d}-\bar{u}$ asymmetry in the proton sea[1]. Actually, the $\bar{d}-\bar{u}$ asymmetry in the nucleon's sea and the consequent Gottfried Sum Rule (GSR)[2] violation were known since the New Muon Collaboration (NMC) experiment in the early 90's[3]. However, the origin of such asymmetry has remained unclear since then.

Several ideas have been put forward to try to explain the GSR violation and the $\bar{d}-\bar{u}$ asymmetry in nucleons. Among them the Pauli exclusion principle, which would inhibit the development of up (down) quarks and anti-quarks in the proton (neutron) sea, a pioneer idea by Field and Feynman[4]; fluctuations of valence quarks into quarks plus massless pions[5], an effect which is calculable in Chiral Field Theory; and earlier versions of the pion cloud model[6]. However, none of these attempts gave a satisfactory description of the experimental data. The major difficulty appears to be the fast fall-off of the $\bar{d}-\bar{u}$ distribution, which albeit large for small x, seems to be negligible beyond $x \sim 0.3$ [1].

In this letter we shall show that a recently proposed version of the Pion Cloud Model (PCM)[7] provides a sensible prediction of the nucleon's $\bar{d}-\bar{u}$ asymmetry measured by the E866/NuSea Collaboration. Our approach is based on both perturbative and effective degrees of freedom and it relies on a recombination model description of the hadronic fluctuations of the nucleon.

Let us briefly recall the model introduced in Ref.[7]. We start by considering a simple picture of the ground state of the proton in the infinite momentum frame as formed by three valence quark clusters or *valons*[8]. The valon distributions in the proton are given by

$$v(x) = \frac{105}{16}\sqrt{x}\,(1-x)^2 \ , \tag{1}$$

where, for simplicity, we do not distinguish between u and d valons.

The higher order contributions to the proton structure are identified with meson-baryon bound states in an expansion of the nucleon wave-function in terms of hadronic Fock states. Such hadronic fluctuations are built up by allowing that a valon emits a gluon which, before interacting with the remaining valons, decays perturbatively into a $q\bar{q}$ pair. This quark anti-quark pair subsequently recombines with the valons so as to form a meson-baryon bound state.

The probability distributions of the initial perturbative $q\bar{q}$ pair can be calculated by means of the Altarelli-Parisi[9] splitting functions:

$$P_{gq}(z) = \frac{4}{3}\frac{1+(1-z)^2}{z}, \qquad P_{qg}(z) = \frac{1}{2}\left(z^2+(1-z)^2\right) . \tag{2}$$

Accordingly, the joint probability density of obtaining a quark or anti-quark coming from subsequent decays $v \to v+g$ and $g \to q+\bar{q}$ at some fixed low Q_v^2 is

$$q(x) = \bar{q}(x) = N\frac{\alpha_{st}^2(Q_v^2)}{(2\pi)^2}\int_x^1 \frac{dy}{y}P_{qg}\left(\frac{x}{y}\right) \int_y^1 \frac{dz}{z}P_{gq}\left(\frac{y}{z}\right)v(z) \ . \tag{3}$$

The value of Q_v, as dictated by the valon model of the nucleon, is about $Q_v = 1$ GeV. For definiteness we take $Q_v = 0.8$ GeV as in Ref.[7,8], which is large enough to allow for a perturbative evaluation of the $q\bar{q}$ pair production. N is a normalization constant whose value depends on the flavor of the quark and anti-quarks produced in the $gq\bar{q}$ vertex.

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Once q and $\bar{q}$ are created, they may subsequently interact with the valons so as to form a most energetically favored meson-baryon bound state. The rearrangement of such five-component nucleon configuration into a meson-baryon bound state must be evaluated by means of effective models. This is necessary because the interactions involved in such a process are within the confinement region of QCD. Therefore, non-perturbative interactions take place. Assuming that the *in-proton* meson and baryon formation arise from similar mechanisms to those at work in the production of real hadrons, we evaluate the in-proton pion probability density using a well-known recombination model approach[10].

Within this scheme, the pion probability density in the $|\pi B\rangle$ fluctuation of the proton is given by

$$P_{\pi B}(x) = \int_0^1 \frac{dy}{y} \int_0^1 \frac{dz}{z} F(y,z) R(x,y,z), \tag{4}$$

where $R(x,y,z)$ is the recombination function associated with the pion formation,

$$R(y,z) = \alpha \frac{yz}{x^2} \delta \left(1 - \frac{y+z}{x}\right) , \tag{5}$$

and $F(y,z)$ is the valon-quark distribution function given by

$$F(y,z) = \beta\, y v(y)\, z\bar{q}(z)(1-y-z)^a . \tag{6}$$

The exponent a in eq. (6) is fixed by the requirement that the pion and the baryon in the $|\pi B\rangle$ fluctuation have the same velocity, thus favoring the formation of the meson-baryon bound state. With the above constraint we obtain $a = 12.9$ and $a = 18$ for the $|\pi^+ n\rangle$ and the $|\pi\Delta\rangle$ fluctuations of the proton respectively.

Note that in the original version of the recombination model this exponent was fixed to 1[10]. This is basically because in a collision, the only relevant kinematical correlation in the model between the initial and final states is momentum conservation. On the other hand, in the present case the recombining quarks are more correlated as they are making part of a single object from the outset. Firstly, meson and baryon must exhaust the momentum of the proton [1], and secondly, they must be correlated in velocity as a bound-state is expected to be formed.

The overall normalization $N\beta\alpha$ of the probability density $P_{\pi B}$ must be fixed by comparison with experimental data.

The non-perturbative $\bar{u}$ and $\bar{d}$ distributions can be now computed by means of the two-level convolution formulas

$$\bar{d}^{NP}(x,Q_v^2) = \int_x^1 \frac{dy}{y} \left[P_{\pi N}(y) + \frac{1}{6} P_{\pi\Delta}(y)\right] \bar{d}_\pi(\frac{x}{y}, Q_v^2) \tag{7}$$

$$\bar{u}^{NP}(x,Q_v^2) = \int_x^1 \frac{dy}{y} \frac{1}{2} P_{\pi\Delta}(y)\ \bar{u}_\pi(\frac{x}{y}, Q_v^2), \tag{8}$$

where the sources $\bar{d}_\pi(x,Q_v^2)$ and $\bar{u}_\pi(x,Q_v^2)$ are the valence quark probability densities in the pion at the low Q_v^2 scale. In eq. (7), we have summed the contributions of the $|\pi^+ n\rangle$ and $|\pi^+\Delta^0\rangle$ fluctuations to obtain the total non-perturbative $\bar{d}$ distribution. For the non-perturbative $\bar{u}$ distribution of eq. (8), the only contribution originates from the $|\pi^-\Delta^{++}\rangle$ fluctuation. We do not include contributions arising from fluctuations containing π^0s because they must be strongly suppressed by the Zweig's rule. We also neglect higher order Fock components.

The factors $\frac{1}{6}$ and $\frac{1}{2}$ in front of $P_{\pi\Delta}$ in eqs. (7) and (8) are the (squared) Clebsh-Gordan (CG) coefficients needed to account for the $\frac{1}{2}$ spin constraint on the fluctuation. The CG coefficient corresponding to the $|\pi^+ n\rangle$ fluctuation is hidden in the global normalization of the state.

We will now compare our results with the experimental data. As the E866/NuSea Collaboration measures the ratio $\bar{d}/\bar{u}$ at $Q = 7.35$ GeV, we first compute this quantity by means of

$$\frac{\bar{d}(x,Q^2)}{\bar{u}(x,Q^2)} = \frac{\bar{d}^{NP}(x,Q^2) + \bar{q}^P(x,Q^2)}{\bar{u}^{NP}(x,Q^2) + \bar{q}^P(x,Q^2)} . \tag{9}$$

Here $\bar{d}^{NP}(x,Q^2)$ and $\bar{u}^{NP}(x,Q^2)$ are given by eqs.(7) and (8) and $\bar{q}^P(x,Q^2)$ represents the perturbative part of the up and down sea of the proton, which we assume to be equal. This assumption is exact up to at least 1%[11].

Regarding the difference $\bar{d} - \bar{u}$, instead of computing it directly by subtracting eqs. (7) and (8), we will extract it from the $\bar{d}/\bar{u}$ ratio as in Ref.[1]. In its paper, the E866/NuSea Collaboration employed the following identity to obtain the difference:

$$\bar{d}(x) - \bar{u}(x) = \frac{\bar{d}(x)/\bar{u}(x) - 1}{\bar{d}(x)/\bar{u}(x) + 1} \left[\bar{u}(x) + \bar{d}(x)\right] . \tag{10}$$

The ratio $\bar{d}(x)/\bar{u}(x)$ is a direct measurement while $\bar{u}(x) + \bar{d}(x)$ is taken from the CTEQ4M parametrization[12].

In Fig. 1, our predictions of $\bar{d}/\bar{u}$ and $\bar{d}-\bar{u}$ are compared with the experimental data from Ref.[1]. The curves were obtained using the pion valence distributions of Ref.[13] in eqs. (7) and (8) and the proton sea quark distributions of Ref.[14] in eq. (9).

[1]We fulfill this requirement by assuming $P_{\pi B}(x) = P_{B\pi}(1-x)$. See Ref.[7] for a discussion about this point.

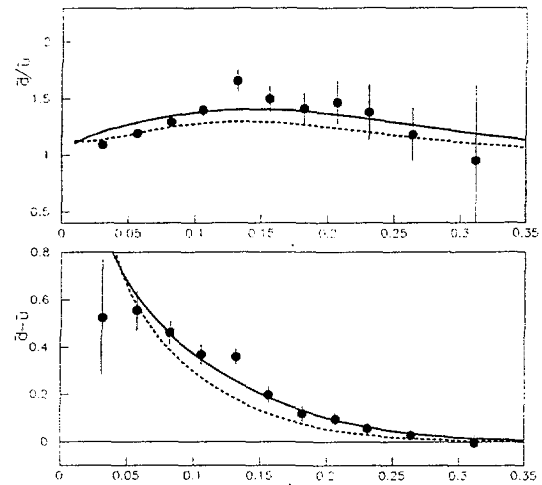

FIG. 1. Predictions of the model compared with experimental data from Ref. [1]. $\bar{d}/\bar{u}$ ratio (upper) and $\bar{d}-\bar{u}$ asymmetry (lower) at $Q = 7.35$ GeV. Curves are calculated with unevolved $\bar{u}^{NP}$ and $\bar{d}^{NP}$ distributions (full line) and with pseudo-evolved non-perturbative distributions (dashed line)

Note that a rigorous comparison of our prediction with the experimental data would require that the non-perturbative $\bar{u}$ and $\bar{d}$ distributions be evolved up to $Q = 7.35$ GeV. Instead of performing a full QCD evolution program, we *pseudo-evolve* the $\bar{u}^{NP}$ and $\bar{d}^{NP}$ distributions by multiplying them by the ratio $q(x, Q^2 = 7.35^2 GeV^2)/q(x, Q_v^2)$. The function q represents the corresponding valence quark distribution in the proton at the E866/NuSea and the valon scales respectively. This simple procedure is satisfactory enough to give us a feeling of the effect of the evolution of the non-perturbative distributions on $\bar{d}/\bar{u}$ and $\bar{d}-\bar{u}$ [2].

As can be seen in Fig. 1, the results of the model are significant. Nevertheless, in the small-x region the model seems to overestimate the value of $\bar{d}-\bar{u}$ due to the steep growth of the valence quark distribution of the pion as $x \to 0$. The effect of the pion structure at low x on $\bar{u}^{NP}$ and $\bar{d}^{NP}$ is too strong. If, for instance, we multiply the valence quark distribution by a power of x, the excessive growth is corrected and the $\bar{d}-\bar{u}$ difference predicted by the model at the valon scale Q_v presents an inflection point about $x \sim 0.05$ and goes to zero with x. The description of the $\bar{d}-\bar{u}$ data is thus improved. In addition, we also get a more accurate description of the $\bar{d}/\bar{u}$ data in all the measured region [see Fig. (2)].

[2]A similar strategy has been adopted in Ref.[15]

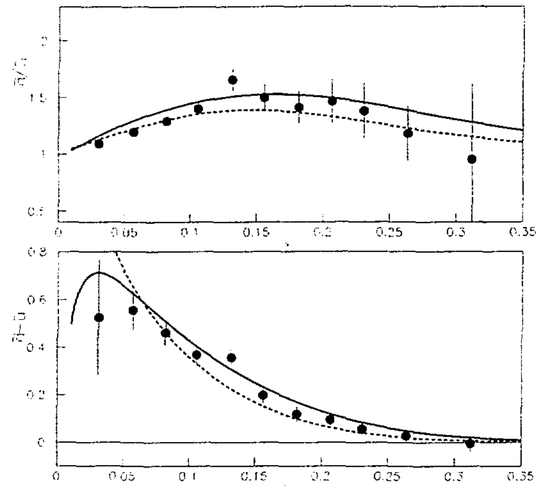

FIG. 2. Same as in Fig. [1] but using a modified valence quark distribution in pions with an extra power of x (normalized accordingly). See discussion in the text.

We obtain similar results by using the low Q^2 pion valence quark distributions of Ref.[16], calculated with a Monte Carlo based model.

It is instructive to look at the integrals of the non-perturbative $\bar{u}$ and $\bar{d}$ distributions in order to get an idea of the relative weights of the $|\pi N\rangle$ and $|\pi\Delta\rangle$ fluctuations in the model. By fixing the normalization of the bound states to fit the experimental data, for the unevolved curves in Fig. 1 (Fig. 2) we have $\int_0^1 dx\, \bar{u}^{NP}(x) \sim 0.28$ (0.15) and $\int_0^1 dx\, \bar{d}^{NP}(x) \sim 0.47$ (0.29). Accordingly, the value of $\int_0^1 dx\, [\bar{u}^{NP}(x) - \bar{d}^{NP}(x)]$ predicted by the model is 0.19 (0.14) [3]. This is in good agreement with the experimental result 0.147 ± 0.039, measured by the NMC[3].

If, on the other hand, we consider the definition of $\bar{u}(x) - \bar{d}(x)$ as given by eq. (10), our prediction of $\int_0^1 dx\, [\bar{u}^{NP}(x) - \bar{d}^{NP}(x)]$ is 0.091 (0.083), in close agreement with 0.1 ± 0.018, obtained by the E866/NuSea Collaboration[1]. Note that this value of the integral is significantly lower than the previous one, which we obtained by direct integration of the difference between eqs. (7) and (8). This discrepancy is due to the modulation introduced by the CTEQ4M $\bar{u}(x) + \bar{d}(x)$ distribution used by the E866/NuSea Collaboration to extract the $\bar{d}-\bar{u}$ distribution [4].

A similar analysis of the E866/NuSea data has been

[3]Notice that, as an integral of a non-singlet quantity, $\int_0^1 dx\, [\bar{d}(x) - \bar{u}(x)]$ is independent of Q^2[5]. Then, our results at the valon scale remain unchanged after QCD evolution.

[4]See also Ref.[1] for an alternative discussion about the discrepancies between E866/NuSea and NMC results.

recently performed in the framework of a light cone form factor version of the pion cloud model[17]. Predictions of this version of the PCM are however not very close to the data. One reason may be the use of unnatural hard pion distributions in $|\pi N\rangle$ and $|\pi\Delta\rangle$ fluctuations, which produce large contributions to the $\bar{u}$ and $\bar{d}$ distributions beyond $x \sim 0.25$. This drawback in the prediction of $\bar{d}-\bar{u}$ translates into the growing behavior of the resulting $\bar{d}/\bar{u}$ ratio. To obtain an improved description of both $\bar{d}-\bar{u}$ and $\bar{d}/\bar{u}$ within this approach, the addition of an *ad-hoc* parametrization of the Pauli exclusion principle is needed. In particular, the Pauli effect is normalized to 7% while the total pion cloud contribution to just 5%. This is a major contrast between this approach and the present work.

Summarizing, we have shown that, including perturbative and effective degrees of freedom in a recombination scheme, a pion cloud model alone closely describes the recent data of the E866/NuSea Collaboration. With just two parameters, the normalization of the $|\pi N\rangle$ and $|\pi\Delta\rangle$ fluctuations, we have presented a significant prediction of the flavor asymmetry in the light nucleon sea. Finally, we have also signaled a possible reason for the apparent discrepancy between E866/NuSea and MNC results on the GSR violation.

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