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Flavor Asymmetry of the Nucleon Sea and the Five-Quark Components of the Nucleons

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The existence of the five-quark Fock states for the intrinsic charm quark in the nucleons was suggested some time ago, but conclusive evidence is still lacking. We generalize the previous theoretical approach to the light-quark sector and study possible experimental signatures for such five-quark states. In particular, we compare the $\bar{d}-\bar{u}$ and $\bar{u}+\bar{d}-s-\bar{s}$ data with the calculations based on the five-quark Fock states. The qualitative agreement between the data and the calculations is interpreted as evidence for the existence of the intrinsic light-quark sea in the nucleons. The probabilities for the $|uudu\bar{u}\rangle$ and $|uudd\bar{d}\rangle$ Fock states are also extracted.

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The possible existence of a significant $uudc\bar{c}$ five-quark Fock component in the proton was proposed some time ago by Brodsky, Hoyer, Peterson, and Sakai (BHPS) [1] to explain the unexpectedly large production rates of charmed hadrons at large forward x_F region. In the light-cone Fock space framework, the probability distribution of the momentum fraction (Bjorken-x) for this nonperturbative "intrinsic" charm (IC) component was obtained [1]. The intrinsic charm originating from the five-quark Fock state is to be distinguished from the "extrinsic" charm produced in the splitting of gluons into $c\bar{c}$ pairs, which is well described by QCD. The extrinsic charm has a "sea-like" characteristics with large magnitude only at the small x region. In contrast, the intrinsic charm is "valence-like" with a distribution peaking at larger x. The presence of the intrinsic charm component can lead to a sizable charm production at the forward rapidity (x_F) region.

The x distribution of the intrinsic charm in the BHPS model was derived with some simplifying assumptions. Recently, Pumplin [2] showed that a variety of light-cone models in which these assumptions are removed would still predict the x distributions of the intrinsic charm similar to that of the BHPS model. The CTEQ collaboration [2] has also examined all relevant hard-scattering data sensitive to the presence of the IC component, and concluded that the existing data are consistent with a wide range of the IC magnitude, from null to 2-3 times larger than the estimate by the BHPS model. This result shows that the experimental data are not yet sufficiently accurate to determine the magnitude or the x distribution of the IC.

In an attempt to further study the role of five-quark Fock states for intrinsic quark distributions in the nucleons, we have extended the BHPS model to the light quark sector and compared the predictions with the experimental data. The BHPS model predicts the probability for the $uudQ\bar{Q}$ five-quark Fock state to be approximately proportional to $1/m_Q^2$, where m_Q is the mass of the quark Q [1]. Therefore, the light five-quark states $uudu\bar{u}$ and $uudd\bar{d}$ are expected to have significantly larger probabilities than the $uudc\bar{c}$ state. This suggests that the light quark sector could potentially provide more clear evidence for the roles of the five-quark Fock states, allowing the specific predictions of the BHPS model, such as the shape of the quark x distributions originating from the five-quark configuration, to be tested.

To compare the experimental data with the prediction based on the intrinsic five-quark Fock state, it is essential to separate the contributions of the intrinsic quark and the extrinsic one. Fortunately, there exist some experimental observables which are free from the contributions of the extrinsic quarks. As discussed later, the $\bar{d}-\bar{u}$ and the $\bar{u}+\bar{d}-s-\bar{s}$ are examples of quantities independent of the contributions from extrinsic quarks. The x distribution of $\bar{d}-\bar{u}$ has been measured in a Drell-Yan experiment [3]. A recent measurement of $s+\bar{s}$ in a semi-inclusive deep-inelastic scattering (DIS) experiment [4] also allowed the determination of the x distribution of $\bar{u}+\bar{d}-s-\bar{s}$. In this paper, we compare these data with the calculations based on the intrinsic five-quark Fock states. The qualitative agreement between the data and the calculations provides evidence for the existence of the intrinsic light-quark sea in the nucleons.

For a $|uudQ\bar{Q}\rangle$ proton Fock state, the probability for quark i to carry a momentum fraction x_i is given in the BHPS model [1] as

$$P(x_1,...,x_5) = N_5 \delta(1-\sum_{i=1}^{5} x_i)[m_p^2 - \sum_{i=1}^{5}\frac{m_i^2}{x_i}]^{-2}, \quad (1)$$

where the delta function ensures momentum conservation. N_5 is the normalization factor for five-quark Fock state, and m_i is the mass of quark i. In the limit of $m_{4,5} >> m_p, m_{1,2,3}$, where m_p is the proton mass, Eq. 1 becomes

$$P(x_1,...,x_5) = \tilde{N}_5 \frac{x_4^2 x_5^2}{(x_4+x_5)^2}\delta(1-\sum_{i=1}^{5} x_i), \quad (2)$$

where $\tilde{N}_5 = N_5/m_{4,5}^4$. Eq. 2 can be readily integrated over x_1, x_2, x_3 and x_4, and the heavy-quark x distribution [1, 2] is:

$$P(x_5) = \frac{1}{2}\tilde{N}_5 x_5^2[\frac{1}{3}(1-x_5)(1+10x_5+x_5^2) - 2x_5(1+x_5)\ln(1/x_5)]. \quad (3)$$

One can integrate Eq. 3 over x_5 and obtain the result $\mathcal{P}_5^{c\bar{c}} = \tilde{N}_5/3600$, where $\mathcal{P}_5^{c\bar{c}}$ is the probability for the $|uudc\bar{c}\rangle$ five-quark Fock state. An estimate of the magnitude of $\mathcal{P}_5^{c\bar{c}}$ was

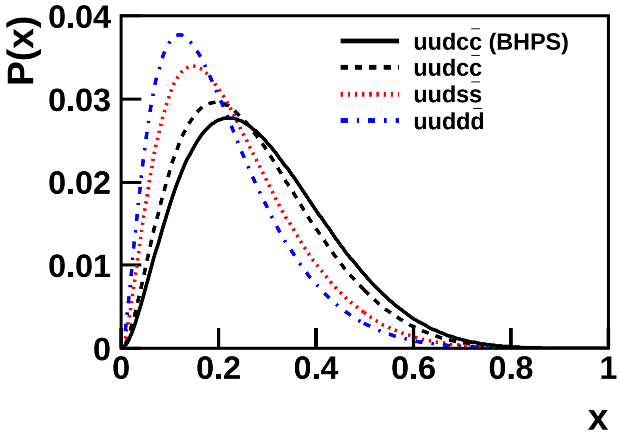

FIG. 1: The x distributions of the intrinsic $\bar{Q}$ in the $uudQ\bar{Q}$ configuration of the proton from the BHPS model [1]. The solid curve is plotted using the expression in Eq. 3 for $\bar{c}$. The other three curves, corresponding to $\bar{c}$, $\bar{s}$, and $\bar{d}$ in the five-quark configurations, are obtained by solving Eq. 1 numerically. The same probability $\mathcal{P}_5^{Q\bar{Q}}$ ($\mathcal{P}_5^{Q\bar{Q}} = 0.01$) is used for the three different five-quark states.

given by Brodsky et al. [1] as ≈ 0.01, based on diffractive production of Λ_c. This value is consistent with a bag-model estimate [5].

The solid curve in Fig. 1 shows the x distribution for the charm quark ($P(x_5)$) using Eq. 3, assuming $\mathcal{P}_5^{c\bar{c}} = 0.01$. Since this analytical expression was obtained for the limiting case of infinite charm-quark mass, it is of interest to compare this result with calculations without such an assumption. To this end, we have developed the algorithm to calculate the quark distributions using Eq. 1 with Monte-Carlo techniques. The five-quark configuration of $\{x_1, ..., x_5\}$ satisfying the constraint of Eq. 1 is randomly sampled. The probability distribution $P(x_i)$ can be obtained numerically with an accumulation of sufficient statistics. We first verified that the Monte-Carlo calculations in the limit of very heavy charm quarks reproduce the analytical result for $P(x_5)$ in Eq. 3. We then calculated $P(x_5)$ using $m_u = m_d = 0.3$ GeV/c^2, $m_c = 1.5$ GeV/c^2, and $m_p = 0.938$ GeV/c^2, and the result is shown as the dashed curve in Fig. 1. The similarity between the solid and dashed curves shows that the assumption adopted for deriving Eq. 3 is adequate. It is important to note that the Monte-Carlo technique allows us to calculate the quark x distributions for other five-quark configurations when Q is the lighter u, d, or s quark, for which one could no longer assume a large mass.

As mentioned above, the insufficient accuracy of existing data as well as the inherently small probability for intrinsic charm due to the large charm-quark mass make it difficult to confirm the existence of the intrinsic charm component in the proton. On the other hand the five-quark states involving only lighter quarks, such as $|uudu\bar{u}\rangle$, $|uudd\bar{d}\rangle$, and $|uuds\bar{s}\rangle$, might be more easily observed experimentally. We have calculated the x distributions of the $\bar{s}$ and $\bar{d}$ quarks in the BHPS model for the $|uuds\bar{s}\rangle$ and $|uudd\bar{d}\rangle$ configurations, respectively, using Eq. 1. The mass of the strange quark is chosen as 0.5 GeV/c^2. In Fig. 1, we show the x distributions of $\bar{s}$ and $\bar{d}$, together with that of $\bar{c}$. In order to focus on the different shapes of the x distributions, the same value of $\mathcal{P}_5^{Q\bar{Q}}$ is assumed for these different five-quark states. Figure 1 shows that the x distributions of the intrinsic $\bar{Q}$ shift progressively to lower x region as the mass of the quark Q decreases. The x distributions of $\bar{Q}$ originating from the gluon splitting into quark-antiquark pair ($g \to Q\bar{Q}$) QCD processes are localized at the low-x region. Figure 1 illustrates an important advantage for identifying the IC component, namely, the intrinsic charm component is better separated from the extrinsic charm component as a result of their different x distributions. Nevertheless, the probability for intrinsic lighter quarks are expected to be significantly larger than for the heavier charm quark. The challenge is to identify proper experimental observables which allow a clear separation of the intrinsic light quark component from the extrinsic QCD component. As we discuss next, the quantities $\bar{d}(x) - \bar{u}(x)$ and $\bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x)$ are suitable for studying the intrinsic light-quark components of the proton.

The first evidence for an asymmetric $\bar{u}$ and $\bar{d}$ distribution came from the observation [6] that the Gottfried Sum Rule [7] was violated. The striking difference between the $\bar{d}$ and $\bar{u}$ distributions was clearly observed subsequently in the proton-induced Drell-Yan [3, 8] and semi-inclusive DIS experiments [9]. This large flavor asymmetry is in qualitative agreement with the meson cloud model which incorporates chiral symmetry [10]. Reviews on this subject can be found in Refs. [11–13].

The $\bar{d}(x) - \bar{u}(x)$ data from the Fermilab E866 Drell-Yan experiment at the Q^2 scale of 54 GeV^2 [3] is shown in Fig. 2.

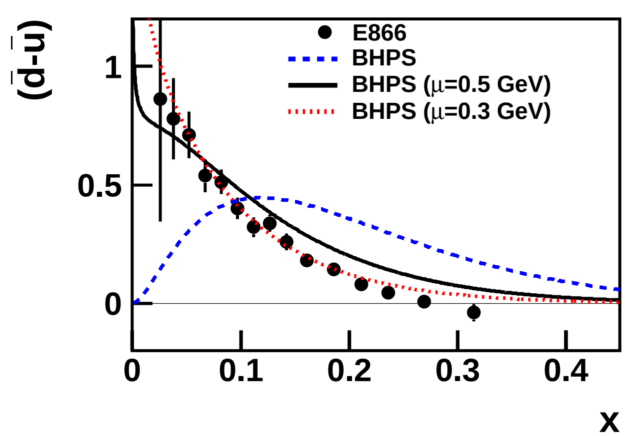

FIG. 2: Comparison of the $\bar{d}(x) - \bar{u}(x)$ data with the calculations based on the BHPS model. The dashed curve corresponds to the calculation using Eq. 1 and Eq. 5, and the solid and dotted curves are obtained by evolving the BHPS result to $Q^2 = 54.0$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively.

The $\bar{d}(x) - \bar{u}(x)$ distribution is of particular interest for testing the intrinsic light-quark contents in the proton, since the perturbative $g \to Q\bar{Q}$ processes are expected to generate $u\bar{u}$ and $d\bar{d}$ pairs with equal probabilities and thus have no contribution to this quantity. In the BHPS model, the $\bar{u}$ and $\bar{d}$ are predicted to have the same x dependence if $m_u = m_d$. It is important to note that the probabilities of the $|uudd\bar{d}\rangle$ and $|uudu\bar{u}\rangle$ configurations, $\mathcal{P}_5^{u\bar{u}}$ and $\mathcal{P}_5^{d\bar{d}}$, are not known from the BHPS model, and remain to be determined from the experiments. Non-perturbative effects such as Pauli-blocking [14] could lead to different probabilities for the $|uudd\bar{d}\rangle$ and $|uudu\bar{u}\rangle$ configurations. Nevertheless the shape of the $\bar{d}(x) - \bar{u}(x)$ distribution shall be identical to those of $\bar{d}(x)$ and $\bar{u}(x)$ in the BHPS model. Moreover, the normalization of $\bar{d}(x) - \bar{u}(x)$ is already known from the Fermilab E866 Drell-Yan experiment as

$$\int_0^1 (\bar{d}(x) - \bar{u}(x))dx = 0.118 \pm 0.012. \quad (4)$$

This allows us to compare the $\bar{d}(x) - \bar{u}(x)$ data with the calculations from the BHPS model, since the above integral is simply equal to $\mathcal{P}_5^{d\bar{d}} - \mathcal{P}_5^{u\bar{u}}$, i.e.

$$\int_0^1 (\bar{d}(x) - \bar{u}(x))dx = \mathcal{P}_5^{d\bar{d}} - \mathcal{P}_5^{u\bar{u}} = 0.118 \pm 0.012. \quad (5)$$

Figure 2 shows the calculation of the $\bar{d}(x) - \bar{u}(x)$ distribution (dashed curve) from the BHPS model, together with the data. The x-dependence of the $\bar{d}(x) - \bar{u}(x)$ data is not in good agreement with the calculation. It is important to note that the $\bar{d}(x) - \bar{u}(x)$ data in Fig. 2 were obtained at a rather large Q^2 of 54 GeV^2 [3]. In contrast, the relevant scale, μ^2, for the five-quark Fock states is expected to be much lower, around the confinement scale. This suggests that the apparent discrepancy between the data and the BHPS model calculation in Fig. 2 could be partially due to the scale dependence of $\bar{d}(x) - \bar{u}(x)$. We adopt the value of $\mu = 0.5$ GeV, which was chosen by Glück, Reya, and Vogt [15] in their attempt to generate gluon and quark distributions in the so-called "dynamical approach" starting with only valence-like distributions at the initial μ^2 scale and relying on evolution to generate the distributions at higher Q^2. We have evolved the predicted $\bar{d}(x) - \bar{u}(x)$ distribution from $Q_0^2 = \mu^2 = 0.25$ GeV^2 to $Q^2 = 54$ GeV^2. Since $\bar{d}(x) - \bar{u}(x)$ is a flavor non-singlet parton distribution, its evolution from Q_0 to Q only depends on the values of $\bar{d}(x) - \bar{u}(x)$ at Q_0, and is independent of any other parton distributions. The solid curve in Fig. 2 corresponds to $\bar{d}(x) - \bar{u}(x)$ from the BHPS model evolved to $Q^2 = 54$ GeV^2. Significantly improved agreement with the data is now obtained. This shows that the x-dependence of $\bar{d}(x) - \bar{u}(x)$ is quite well described by the five-quark Fock states in the BHPS model provided that the Q^2-evolution is taken into consideration. It is interesting to note that an excellent fit to the data can be obtained if $\mu = 0.3$ GeV is chosen (dotted curve in Fig. 2) rather than the more conventional value of $\mu = 0.5$ GeV. We have also found good agreement between the HERMES $\bar{d}(x) - \bar{u}(x)$ data at $Q^2 = 2.3GeV^2$ [9] with calculation using the BHPS model.

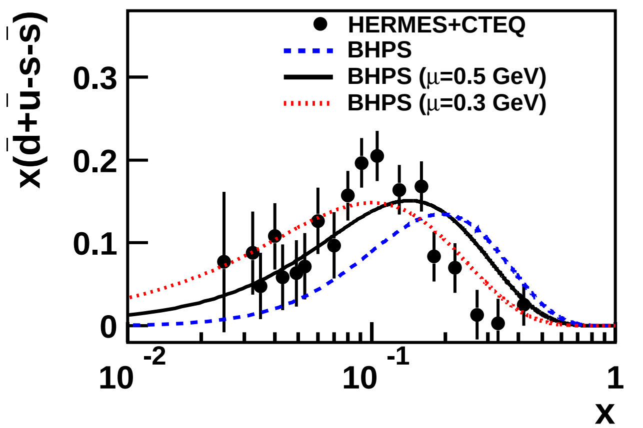

FIG. 3: Comparison of the $x(\bar{d}(x) + \bar{u}(x) - s(x) - \bar{s}(x))$ data with the calculations based on the BHPS model. The dashed curve corresponds to the calculation using Eq. 1, and the solid and dotted curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively.

We now consider the quantity $\bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x)$. New measurements of charged kaon production in semi-inclusive DIS by the HERMES collaboration [4] allow the extraction of $x(s(x) + \bar{s}(x))$ at $Q^2 = 2.5$ GeV^2. Combining this result with the $x(\bar{d}(x) + \bar{u}(x))$ distributions determined by the CTEQ group (CTEQ6.6) [16], the quantity $x(\bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x))$ can be obtained and is shown in Fig. 3. This approach for determining $x(\bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x))$ is identical to that used by Chen, Cao, and Signal in their recent study [17] of strange quark sea in the meson-cloud model [18].

An interesting property of $\bar{u} + \bar{d} - s - \bar{s}$ is that the contribution from the extrinsic sea vanishes, just like the case for $\bar{d} - \bar{u}$. Therefore, this quantity is only sensitive to the intrinsic sea and can be compared with the calculation of the intrinsic sea in the BHPS model. We have

$$\bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x) = \\ P^{u\bar{u}}(x_{\bar{u}}) + P^{d\bar{d}}(x_{\bar{d}}) - 2P^{s\bar{s}}(x_{\bar{s}}), \quad (6)$$

where $P^{Q\bar{Q}}(x_{\bar{Q}})$ is the x-distribution for $\bar{Q}$ in the $|uudQ\bar{Q}\rangle$ Fock state. Although the shapes of the intrinsic $\bar{u}, \bar{d}, s, \bar{s}$ distributions can be readily calculated from the BHPS model, the relative magnitude of the intrinsic strange sea versus intrinsic non-strange sea is unknown. We have adopted the assumption that the probability of the intrinsic sea is proportional to $1/m_Q^2$, as stated earlier. This implies that $\mathcal{P}_5^{s\bar{s}}/(\frac{1}{2}(\mathcal{P}_5^{u\bar{u}} + \mathcal{P}_5^{d\bar{d}})) = m_{\bar{u}}^2/m_{\bar{s}}^2 \approx 0.36$ for $m_{\bar{u}} = 0.3$ GeV/c^2 and $m_{\bar{s}} = 0.5$ GeV/c^2. With this assumption, we can now compare the $x(\bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x))$ data with the calculation using the BHPS model, shown as the dashed curve in Fig. 3. The prediction of the BHPS model is found to be shifted to larger x relative to the data. This apparent discrepancy could again partially reflect the different scales of the theory and the data. Since $\bar{u}+\bar{d}-s-\bar{s}$ is a flavor non-singlet quantity, we can readily evolve the BHPS prediction to $Q^2 = 2.5$ GeV^2 using $Q_0 = \mu = 0.5$ GeV and the result is shown as the solid curve in Fig. 3. Better agreement between the data and the calculation is achieved after the scale dependence is taken into account. It is interesting to note that a better fit to the data can again be obtained with $\mu = 0.3$ GeV, shown as the dotted curve in Fig. 3.

From the comparison between the data and the BHPS calculation using $\mu = 0.5$ GeV in Fig. 3, one can determine the sum of the probabilities for the $|uudu\bar{u}\rangle$ and $|uudd\bar{d}\rangle$ configurations, $\Sigma\mathcal{P}_5^{\bar{d}\bar{u}}$ ($= \mathcal{P}_5^{d\bar{d}} + \mathcal{P}_5^{u\bar{u}}$). We found that $\Sigma\mathcal{P}_5^{\bar{d}\bar{u}} = 0.471$. Together with Eq. 5, we have

$$\mathcal{P}_5^{u\bar{u}} = 0.176; \quad \mathcal{P}_5^{d\bar{d}} = 0.294. \tag{7}$$

It is remarkable that the $\bar{d}(x) - \bar{u}(x)$ and the $\bar{d}(x) + \bar{u}(x) - s(x) - \bar{s}(x)$ data not only allow us to check the predicted x-dependence of the five-quark $|uudu\bar{u}\rangle$ and $|uudd\bar{d}\rangle$ Fock states, but also provide a determination of the probabilities for these two states. As expected, the extracted values for the five-quark Fock states probabilities in Eq. 7 depends on the assumption for the probability of the $|uuds\bar{s}\rangle$. For the limiting case of $\mathcal{P}_5^{s\bar{s}} = 0$, we obtain $\mathcal{P}_5^{u\bar{u}} = 0.097$ and $\mathcal{P}_5^{d\bar{d}} = 0.215$, which reflect the range of uncertainty of the extracted values. It is interesting to note that values obtained in Eq. 7 are consistent with the $1/m_Q^2$ assumption for the probability of the $|uudQ\bar{Q}\rangle$ Fock state. If one uses the bag model estimate of $\mathcal{P}_5^{c\bar{c}} \sim 0.01$ [5], the $1/m_Q^2$ dependence would then imply that $\mathcal{P}_5^{d\bar{d}}$ to be $\sim 0.01(m_c^2/m_d^2) \sim 0.25$, consistent with the results of Eq. 7.

In conclusion, we have generalized the existing BHPS model to the light-quark sector and compared the calculation with the $\bar{d}-\bar{u}$ and $\bar{u}+\bar{d}-s-\bar{s}$ data. The qualitative agreement between the data and the calculation provides strong supports for the existence of the intrinsic u and d quark sea and the adequacy of the BHPS model. This analysis also led to the determination of the probabilities for the five-quark Fock states for the proton involving light quarks only. This result could guide future experimental searches for the intrinsic s and c quark sea. This analysis could also be readily extended to the hyperon and meson sectors. The connection between the BHPS model and other multi-quark models [19, 20] should also be investigated.

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