THE FLAVOR STRUCTURE OF THE NUCLEON SEA

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Abstract

We discuss two topics related to the flavor structure of the nucleon sea. The first is on the identification of light-quark intrinsic sea from the comparison between recent data and the intrinsic sea model by Brodsky et al. Good agreement between the theory and data allows a separation of the intrinsic from the extrinsic sea components. The magnitudes of the up, down, and strange intrinsic seas have been extracted. We then discuss the flavor structure and the Bjorken-\(x\) dependence of the connected sea (CS) and disconnected sea (DS). We show that recent data together with input from lattice QCD allow a separation of the CS from the DS components of the light quark sea.

1 Introduction

The flavor structure of the nucleon sea can provide new insight on the nature of QCD at the confinement scale. Perturbative QCD predicts a largely flavor symmetric \(\bar{u}, \bar{d}, \bar{s}\) sea, as the \(g \to Q\bar{Q}\) process, in which a gluon split into a quark antiquark pair \((Q\bar{Q})\), is insensitive to the current-quark masses of the \(u, d, s\), which are small relative to the QCD scale. Indeed, in the 1980s, it was commonly assumed that the nucleon’s sea is \(\bar{u}, \bar{d}, \bar{s}\) flavor symmetric, notwithstanding the fact that ideas based on meson-cloud \([1]\), Pauli-blocking \([2]\), and intrinsic sea \([3]\), already led to predictions of a flavor asymmetric nucleon sea. We emphasize that the term “flavor asymmetry” does not imply that any fundamental symmetry principle is violated, it merely refers to the differences between the \(\bar{u}, \bar{d}, \bar{s}\) sea quark distributions in the proton.

The earliest evidences for a flavor asymmetric nucleon sea came from the observation of possible violation of the Gottfried sum rule, suggesting \(\bar{u} \neq \bar{d}\), and the charm production in neutrino-induced deep-inelastic scattering (DIS), showing that strange quark sea is suppressed relative to the up and down quark seas. This topics continues to attract intense theoretical and experimental interest. We discuss some recent progress in our understanding of the flavor structure of the nucleon sea. We first present the recent analysis which leads to a determination of the intrinsic sea components for \(\bar{u}, \bar{d}, \bar{s}\) in the proton. We then discuss some recent effort to interpret the flavor structure and momentum dependence of sea quark distributions in the context of connected and disconnected seas in the framework of lattice QCD.
2 Intrinsic versus extrinsic sea

Brodsky, Hoyer, Peterson, and Sakai (BHPS) proposed some time ago that the $|uudcc\rangle$ five-quark Fock state in the proton can lead to enhanced production rates for charmed hadrons at forward rapidity region $\tilde{x}$. The $cc$ component in the $|uudcc\rangle$ configuration is coined “intrinsic” sea in order to distinguish it from the conventional “extrinsic” sea originating from the $g \to c\bar{c}$ QCD process. The maximal probability for the $uudc\bar{c}$ Fock state occurs when all five quarks move with similar velocities. The larger mass of the charmed quark implies that the $c$ and $\bar{c}$ quarks would carry a large fraction of proton’s momentum. This leads to the expectation that the intrinsic charm has a momentum distribution which is valence-like, peaking at relatively large $x$. In contrast, the extrinsic charm, which results from gluon splitting, is dominant at the small $x$ region. While some tantalizing evidences for intrinsic charm have been reported, a study by the CTEQ Collaboration [4] concluded that the existing data are not yet sufficiently accurate to confirm or refute the existence of intrinsic charm.

It is natural to pose the question, “are there any evidences for intrinsic sea of lighter quarks, i.e., the $|uud\bar{u}\rangle$, $|uudd\bar{d}\rangle$, and $|uud\bar{s}\bar{s}\rangle$ Fock states?”. In the BHPS model, the probability for the $|uud\bar{Q}\bar{Q}\rangle$ Fock state is expected to be roughly proportional to $1/m_Q^2$, where $m_Q$ is the mass of quark $Q$. This suggests significantly larger probabilities for these light-quark intrinsic sea than for the intrinsic charm. Therefore, it is potentially easier to find evidences for these light-quark intrinsic sea. The challenge, however, is to come up with ways to disentangle the intrinsic sea from the more abundant extrinsic sea.

In a recent attempt to search for evidences for intrinsic light-quark sea, two approaches were adopted in order to disentangle the intrinsic from the extrinsic sea [5]. The first approach is to select experimental observables which have either very little or no contributions from the extrinsic sea. The other approach is to rely on the different dependences for the intrinsic and extrinsic seas. As mentioned earlier, the intrinsic sea is valence-like and is more abundant at large $x$ while the extrinsic sea is dominant at the small $x$ region.

One example of an observable free from the contribution of the extrinsic sea is $\bar{d}(x) - \bar{u}(x)$. The perturbative $g \to Q\bar{Q}$ process is expected to generate $u\bar{u}$ and $d\bar{d}$ pairs with equal probability and would have no contribution to $\bar{d}(x) - \bar{u}(x)$. Figure 1 shows the $\bar{d}(x) - \bar{u}(x)$ data from the Fermilab E866 Drell-Yan experiment [6] in comparison with the calculation using the BHPS model. The $\bar{u}$ and $\bar{d}$ are predicted to have identical $x$ dependence if $m_u = m_d$. The exact values for the probabilities of the $|uudd\bar{d}\rangle$ and $|uuud\bar{u}\rangle$ configuration, $P_5^{d\bar{d}}$ and $P_5^{u\bar{u}}$, are not predicted by the BHPS model and must be determined from experiments. However, the difference between $P_5^{d\bar{d}}$ and $P_5^{u\bar{u}}$ is known from the moment of $\bar{d}(x) - \bar{u}(x)$, namely,
\[ \int_0^1 (\bar{d}(x) - \bar{u}(x))dx = P_5^{\bar{d}d} - P_5^{\bar{u}u} = 0.118 \pm 0.012, \]  

(1)

where the moment is evaluated using the \( \bar{d}(x) - \bar{u}(x) \) data from the Fermilab E866 experiment. Figure 1 compares the \( \bar{d}(x) - \bar{u}(x) \) data with the calculation (dashed curve) using the BHPS model and the constraint given by Eq. (1). The BHPS calculation is in apparent disagreement with the \( \bar{d}(x) - \bar{u}(x) \) data. However, the relevant scale, \( \mu \), for the BHPS model calculation is at the confinement scale, which is much lower than the \( Q^2 = 54 \text{ GeV}^2 \) scale of the E866 data. It is therefore necessary to evolve the BHPS result from the initial scale to \( Q^2 = 54 \text{ GeV}^2 \). Figure 1 shows that good agreement between the calculation (solid curve) and the data is achieved when the initial scale is chosen as \( \mu = 0.5 \text{ GeV} \). Note that an even better agreement with the data is obtained by lowering the initial scale to \( \mu = 0.3 \text{ GeV} \).

An example for identifying the intrinsic sea component by making use of its valence-like \( x \) distribution has been reported recently \[7\]. Figure 2 shows the extraction of \( x(s(x) + \bar{s}(x)) \) from a measurement of charged kaon production in semi-inclusive DIS by the HERMES Collaboration \[5\]. An intriguing feature of Fig. 2 is that the strange sea falls off rapidly with \( x \) for \( x < 0.1 \), and becomes a broad peak at the large \( x \) region. The HERMES result suggests the presence of two distinct components of the strange sea, one at the small \( x \) (\( x < 0.1 \)) region and another centered at the larger \( x \) region. This is in qualitative agreement with the expectation that extrinsic and intrinsic seas have dominant contributions at small and large \( x \) region, respectively. A comparison between the data and calculations using the BHPS model is shown in Fig. 2 for \( \mu = 0.5 \) and \( \mu = 0.3 \text{ GeV} \). The data at \( x > 0.1 \) are quite well described by the calculations, supporting the interpretation that the \( x(s(x) + \bar{s}(x)) \) in the valence region is dominated by the intrinsic sea. From the normalization of the BHPS calculations shown in Fig. 2, one can extract the probability of the \( |uud\bar{s}\bar{s}| \) as

\[ P_5^{uud\bar{s}\bar{s}} = 0.024 \quad (\mu = 0.5 \text{ GeV}); \quad P_5^{uud\bar{s}\bar{s}} = 0.029 \quad (\mu = 0.3 \text{ GeV}). \]  

(2)

Another quantity which is largely free from the extrinsic sea is \( \bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x) \). Under the assumption that the perturbative \( g \rightarrow Q\bar{Q} \) process leads to \( \bar{u}, \bar{d}, \bar{s} \) flavor symmetric sea, only the intrinsic sea component can contribute to \( \bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x) \). From the HERMES measurement of \( x(s(x) + \bar{s}(x)) \) and the \( x(\bar{u}(x) + \bar{d}(x)) \) from the CTEQ6.6 PDF \[9\], we obtain \( x(\bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x)) \) as shown in Fig. 3. We note that Chen, Cao, and Signal \[10\] have also examined this quantity earlier in the context of the meson-cloud model. Figure 3 shows a remarkable feature that the \( x(\bar{u} + \bar{d} - s - \bar{s}) \) distribution is valence-like and peaking at \( x \sim 0.1 \). One can compare it with the BHPS
model calculation using the following expression

\[ x(\bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x)) = x(P_{u\bar{u}}(x_{u\bar{u}}) + P_{d\bar{d}}(x_{d\bar{d}}) - 2P_{s\bar{s}}(x_{s\bar{s}})), \tag{3} \]

where \( P^{Q\bar{Q}}(x_{Q}) \) is the \( x \) distribution of \( \bar{Q} \) in the \( |uudQ\bar{Q}\rangle \) Fock state. Since the quantity \( \bar{u} + \bar{d} - s - \bar{s} \) is flavor non-singlet, it can be readily evolved from the initial scale \( \mu \) to \( Q^2 = 2.5 \) GeV\(^2\). Figure 3 shows a good agreement between the BHPS model calculation and the data. From the comparison between the BHPS calculations and the data shown in Figs. 1-3, the probabilities for the \( |uudu\bar{u}\rangle, |uudd\bar{d}\rangle, |uuds\bar{s}\rangle \) Fock states can be determined as follows (using \( \mu = 0.5 \) GeV):

\[ P_{5}^{u\bar{u}} = 0.122; \quad P_{5}^{d\bar{d}} = 0.240; \quad P_{5}^{s\bar{s}} = 0.024. \tag{4} \]

It is remarkable that the existing data on \( \bar{d}(x) - \bar{u}(x), s(x) + \bar{s}(x), \) and \( \bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x) \) not only provide a test of the BHPS model on the intrinsic sea, but also allow an extraction of the probabilities of various five-quark Fock states involving light antiquarks. This result could also be extended to possible future studies on some related topics. Some examples of these topics include:

- **Search for intrinsic charm and beauty.** From the expectation that the probability for the \( |uudQ\bar{Q}\rangle \) Fock state is proportional to \( 1/m_{Q}^2 \) and from the values listed in Eq. (4), one can readily estimate that the probability for the intrinsic charm \( |uudc\bar{c}\rangle \) Fock state, \( P_{5}^{c\bar{c}} \), to be roughly \( (m_{s}^2/m_{c}^2)P_{5}^{s\bar{s}} \sim 0.003 \), which is smaller than earlier estimate \[3\]. Therefore, future measurements with higher precision, possibly at RHIC and LHC, would be very valuable.

- **Search for intrinsic gluons.** The Fock state \( |uudg\rangle \) would provide a valence-like gluon component in the proton \[11\]. It remains a challenge to identify experimental signatures for such valence-like gluons.
Spin and transverse-momentum dependent observables of intrinsic sea. Only the spin-averaged distributions for the intrinsic sea has been considered so far. It would be very interesting to explore the implications of intrinsic sea on the spin-dependent and possibly transverse-momentum dependent parton distributions of the proton.

Intrinsic sea for mesons and hyperons. It is straightforward to extend the formulation for the nucleon’s intrinsic sea to the cases for mesons and hyperons. The presence of these valence-like seas could affect, for example, the meson- or hyperon-induced Drell-Yan cross sections in the forward rapidity region.

Connection between the intrinsic sea and other models. It is important to understand the similarities and differences between the BHPS intrinsic sea model and other theoretical models such as the meson-cloud model \[12\] and the multi-quark model \[13\]. Some recent study \[14\] has been carried out to elucidate the connection between the intrinsic/extrinsic seas and the connected/disconnected seas in the lattice QCD formulatio, as discussed next.

3 Connected versus disconnected sea

In order to gain further insight on the flavor structure of the nucleon sea, we note that, according to the path-integral formalism of the hadronic tensor, there are two distinct sources of nucleon sea, namely, the connected sea (CS) and the disconnected sea (DS). Figure 4 shows the two diagrams for the connected and disconnected seas. In Fig. 4 (a), the quark line propagating backward in time between \(t_1\) and \(t_2\) corresponds to the connected-sea antiquarks \(\bar{q}^{CS}\) (\(\bar{u}^{CS}\) or \(\bar{d}^{CS}\)), which have the same flavors as the valence quarks. Figure 4 (b) shows the DS component \(q^{DS}\) and \(\bar{q}^{DS}\) for \(q = u, d, s, c\). These two different sources of sea quarks have distinct quark flavor and \(x\)-dependence \[14\]. While the \(\bar{u}\) and \(\bar{d}\) seas can originate from both the CS and DS, only DS is present for the \(s(\bar{s})\) and \(c(\bar{c})\) sea. At the small-\(x\) region, the CS and DS are also expected to have different \(x\) dependences. Since only reggeon exchange occurs for CS, one expects \(\bar{q}^{CS} \propto x^{-1/2}\) at small \(x\). The presence of pomeron exchange implies that \(\bar{q}^{DS} \propto x^{-1}\) at small \(x\).

The distinct \(x\) dependences of CS and DS remain to be checked experimentally. Since \(s\) and \(\bar{s}\) sea is entirely originating from the DS, the HERMES measurement of \(s(x) + \bar{s}(x)\) provides valuable information on the shape of the \(x\) dependence for the DS, which is not yet available from lattice QCD calculations. The \(\bar{u}\) and \(\bar{d}\) seas contain contributions from both the CS and DS. It is of interest to separate these two components. A first
Figure 5: Decomposition of \( x(\bar{u}(x) + \bar{d}(x)) \) into the connected sea (CS) and the disconnected sea (DS) components using the procedure described in the text. The CT10 parametrization of \( x(\bar{u}(x) + \bar{d}(x)) \) is also shown.

An attempt to separate the CS from the DS was reported for the \( \bar{u} + \bar{d} \) sea using the following approach [14]. First, a plausible ansatz that \( \bar{u}_{DS}(x) + \bar{d}_{DS}(x) \) is proportional to \( s_{DS}(x) + \bar{s}_{DS}(x) \) (or equivalently, \( s(x) + \bar{s}(x) \), since only DS contributes to strange sea) is adopted. A recent lattice calculation [15] gives the ratio \( R \) for the moment of the strange quarks over that of the \( \bar{u} \) plus \( \bar{d} \) for the disconnected diagram as

\[
R = \frac{\langle s(x) + \bar{s}(x) \rangle}{\langle \bar{u}_{DS + \bar{d}_{DS}}(x) \rangle} = 0.857(40). \tag{5}
\]

Therefore, one can readily separate the CS and DS components for \( \bar{u}(x) + \bar{d}(x) \) as follows:

\[
\bar{u}_{DS}(x) + \bar{d}_{DS}(x) = \frac{1}{R}(s(x) + \bar{s}(x)) \tag{6}
\]

and

\[
\bar{u}_{CS}(x) + \bar{d}_{CS}(x) = \bar{u}(x) + \bar{d}(x) - \frac{1}{R}(s(x) + \bar{s}(x)). \tag{7}
\]

Figure 5 shows the decomposition of \( x(\bar{u}(x) + \bar{d}(x)) \) into the CS and DS components, using Eqs. (6) and (7). The \( x \) dependences for CS and DS are very different and are in qualitative agreement with the expectation discussed earlier. This agreement lends support to the ansatz and approach adopted in this analysis.

From Fig. 5 one could also calculate the momentum fractions carried by the CS and DS. It is interesting that the momentum fraction of the \( \bar{u}(x) + \bar{d}(x) \) is roughly equally divided between the CS and DS at \( Q^2 = 2.5 \text{ GeV}^2 \). We also note that in a very recent work [16], the possible sign-change of \( \bar{d}(x) - \bar{u}(x) \) at \( x \sim 0.3 \) as well as a qualitative explanation for this sign-change in the context of lattice QCD are discussed.

The formulation of CS and DS can also explain qualitatively the \( x \) dependence of the \( R(x) = (s(x) + \bar{s}(x))/(\bar{u}(x) + \bar{d}(x)) \) ratio. Figure 6 shows the ratio \( R(x) \) from some recent PDF sets [17]. While \( R(x) \) is roughly constant at the small \( x \) region, it falls with increasing \( x \) in the region \( 0.01 < x < 0.3 \). At small \( x \), the DS component is expected to dominate, due to its \( x^{-1} \) dependence. Therefore, it is expected that \( R \to 0.857 \) at small
Figure 6: Ratio of $s + \bar{s}$ over $\bar{u} + \bar{d}$ versus $x$ at $Q^2 = 5$ GeV$^2$ from various recent PDFs [17].

$x$, according to the lattice QCD calculation for the DS [15]. The recent measurement of $W$ and $Z$ boson productions in $pp$ collision at 7 TeV by the ATLAS Collaboration gives $r_s = (s + \bar{s})/2\bar{d}$ at $x = 0.023$ to be $1.0 + 0.25 - 0.28$ [18]. Both the CTEQ6.6 and ATLAS result are consistent with a roughly $\bar{u}, \bar{d}, \bar{s}$ flavor symmetric sea at small $x$. At the larger $x$ region, the valence-like CS can contribute to $\bar{u}$ and $\bar{d}$, but not to $s$ and $\bar{s}$. This results in smaller values of $R(x)$ at larger $x$. It is expected that future $W$ and $Z$ production data as well as semi-inclusive kaon production data would further improve our knowledge on the $x$ dependence of the strange quark sea.

4 Conclusion

In summary, we have generalized the BHPS model to the light-quark sector and compared the model calculations with the $\bar{d} - \bar{u}$, $s + \bar{s}$, and $\bar{u} + \bar{d} - s - \bar{s}$ data. The qualitative agreement between the data and the calculations provides strong evidence for the existence of the intrinsic $u$, $d$, $s$ quark sea. This analysis also allows the extraction of the probabilities for these Fock states. The concept of connected and disconnected seas in lattice QCD offers new insights on the flavor and $x$ dependences of the nucleon sea. Ongoing and future Drell-Yan (and $W/Z$ production) and semi-inclusive DIS experiments will provide new information on the flavor structure of the nucleon sea.

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