Probing $\bar{u}/\bar{d}$ Asymmetry in the Proton via Quarkonium Production

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Abstract

The sensitivity of proton-induced $J/\psi$ and $\Upsilon$ production to the possible $\bar{u}/\bar{d}$ asymmetry in the nucleon is studied. The ratio of the quarkonium production cross sections at large $x_F$ on hydrogen over deuterium targets, $\sigma(p+p)/\sigma(p+d)$, is shown to be sensitive to this asymmetry. Predictions of various theoretical models for this ratio are presented.
The New Muon Collaboration (NMC) reported [1] the result of their measurement of the Gottfried Sum [2] in muon deep inelastic scattering (DIS). The Gottfried Sum is given as

$$I_G(x_1, x_2; Q^2) = \int_{x_1}^{x_2} dx \frac{(F_{2\mu p}(x, Q^2) - F_{2\mu n}(x, Q^2))/x}{x}, \quad (1)$$

where $F_{2\mu p}$ and $F_{2\mu n}$ are the proton and neutron structure functions measured in muon DIS. Assuming charge symmetry for the parton distributions in the proton and neutron, $F_2$ can be expressed in terms of the valence and sea quark distributions of the proton. The Gottfried Sum becomes

$$I_G(x_1, x_2; Q^2) = \frac{1}{3} \int_{x_1}^{x_2} dx [u(x, Q^2) - d(x, Q^2)] + \frac{2}{3} \int_{x_1}^{x_2} dx [\bar{u}(x, Q^2) - \bar{d}(x, Q^2)]. \quad (2)$$

The integral in the first term of (2) gives the difference between the number of the up and down valence quarks in the proton. The second term in (2) vanishes under the assumption of a $\bar{u} - \bar{d}$ flavor-symmetric sea for the proton, and the Gottfried Sum Rule (GSR) [2]

$$I_G(0, 1; Q^2) = \frac{1}{3} \quad (3)$$

is obtained. Based on their measurements of muon DIS on hydrogen and deuterium targets, the NMC has determined $I_G(0.004, 0.8; Q^2 = 4 GeV^2) = 0.227 \pm 0.007$ [1]. Following an extrapolation to the unmeasured $x$-region, it was estimated $I_G(0, 1; Q^2 = 4 GeV^2) = 0.240 \pm 0.016$, significantly different from 1/3.

Many theoretical models [3-13] have been proposed to account for the apparent violation of the GSR. These models in general fall into two categories. Models in the first category [3,4] assume that the valence quark distributions in the proton are sufficiently singular at $x < 0.004$ such that a large contribution to the Gottfried Sum occurs at this region not probed by the NMC experiment. Therefore, the GSR is not violated and the assumption of $\bar{u}/\bar{d}$ symmetry in the proton remains valid in these models. The other category of theoretical models [5-13] interpret the NMC result as evidence that the $\bar{u}$ and $\bar{d}$ distributions in the proton are different. Some empirical expressions for $\bar{d}(x) - \bar{u}(x)$ have been proposed [6,9,13]. Several recent sets of parton distribution functions [14,15] explicitly allow $\bar{u}/\bar{d}$ asymmetry to account for the NMC result. The origin of the enhancement of $\bar{d}$ over $\bar{u}$ in the proton has been attributed to pion cloud [3,8,12], diquark clustering in the nucleon [10], as well as Pauli-blocking effect [11].

It has been proposed [6,16,17] that the Drell-Yan process provides an independent and sensitive test of the possible $\bar{u}/\bar{d}$ asymmetry in the proton. Using a proton beam and restricting the kinematic regime to forward $x_F$ ($x_F > 0.2$), it is straightforward to show that...
\[2^{\frac{\sigma_{DY}(p+p)}{\sigma_{DY}(p+d)}} \approx 1 - \frac{\bar{d}_p(x) - \bar{u}_p(x)}{\bar{d}_p(x) + \bar{u}_p(x)},\]  
A similar expression with a reduced sensitivity to the \(\bar{u}/\bar{d}\) asymmetry can also be obtained for the ratio of Drell-Yan cross sections on neutron-rich targets versus isoscalar targets. In fact, the E772 Drell-Yan data [18] obtained with tungsten and isoscalar targets have been compared with predictions from various models. More recently, the NA51 experiment [19] reported \(\frac{\sigma_{DY}(p+p)}{\sigma_{DY}(p+d)} = 0.91 \pm 0.02 \pm 0.02\) measured at 450 GeV near \(x_F \simeq 0\) and \(x = 0.18\). The NA51 result shows a significant asymmetry of \(\bar{u}\) and \(\bar{d}\) in the proton. Another Drell-Yan experiment covering a wider \(x\) range (0.05 < \(x\) < 0.3) at 800 GeV has also been proposed [20].

In addition to the DIS and the Drell-Yan processes, there are other interactions sensitive to the sea-quark distributions in the nucleon. Of particular interest is the hadronic production of \(J/\psi\) and \(\Upsilon\), which can be detected in the same experiments designed to measure the Drell-Yan process. In this paper, the sensitivity of \(J/\psi\) and \(\Upsilon\) production to the sea quark distributions in the nucleon is studied.

In contrast to the electromagnetic Drell-Yan process, hadronic \(J/\psi\) and \(\Upsilon\) production involves strong interactions. The two processes responsible for producing a pair of heavy quarks (\(c\bar{c}\) and \(b\bar{b}\)) are the \(q\bar{q}\) annihilation and \(gg\) fusion. The cross sections for these QCD subprocesses are [21]

\[
\sigma(q\bar{q} \to Q\bar{Q}; m^2) = \frac{8\pi\alpha_s^2}{27m^6}(m^2 + 2m_Q^2)\lambda,
\]

\[
\sigma(gg \to Q\bar{Q}; m^2) = \frac{\pi\alpha_s^2}{3m^6}\{(m^4 + 4m^2m_Q^2 + m_Q^4)\ln\left(\frac{m^2 + \lambda}{m^2 - \lambda}\right) - \frac{1}{4}(7m^2 + 31m_Q^2)\lambda\},
\]

where \(m\) is the invariant mass of the heavy quark pair (\(Q\bar{Q}\)), \(m_Q\) is the heavy quark mass and \(\lambda = (m^4 - 4m^2m_Q^2)^{1/2}\). According to the QCD factorization theorem, the differential cross section for producing a \(Q\bar{Q}\) pair in hadronic interaction is

\[
\frac{d\sigma}{dx_F d\tau} = \frac{2\tau}{(x_F^2 + 4\tau^2)^{1/2}}H_{PT}(x_1, x_2; m^2),
\]

where \(x_1, x_2\) are the fractional momenta carried by the projectile (\(P\)) partons and target (\(T\)) partons, respectively, \(x_F = x_1 - x_2\) and \(\tau^2 = m^2/S\). \(H_{PT}\) is the convolution of parton cross sections and the parton distribution functions in the projectile and target hadrons

\[
H_{PT}(x_1, x_2; m^2) = G_P(x_1)G_T(x_2)\sigma(q\bar{q} \to Q\bar{Q}; m^2) + \sum_{i=u,d,s} \{q_i^P(x_1)\bar{q}_i^T(x_2) + \bar{q}_i^P(x_1)q_i^T(x_2)\}\sigma(q\bar{q} \to Q\bar{Q}; m^2),
\]
$G(x), q(x), \text{ and } \overline{q}(x)$ signify the gluon, quark, and antiquark distribution functions respectively.

To go from the production of $Q\overline{Q}$ pair to the production of $Q\overline{Q}$ bound states, we use the semi-local duality model \[22\]. In this model, the $Q\overline{Q}$ bound state cross section is obtained by integrating the free $Q\overline{Q}$ cross section over $\tau$ from the $Q\overline{Q}$ threshold, $\tau_1 = 2m_Q/\sqrt{s}$, to the open charm (or beauty) threshold, $\tau_2 = 2m_{D(B)}/\sqrt{s}$. Hence

$$d\sigma/dx_F(J/\psi, \Upsilon) = F \int_{\tau_1}^{\tau_2} 2\tau d\tau H_{PT}(x_1, x_2; m^2)/(x_F^2 + 4\tau^2)^{1/2}, \tag{8}$$

where $F$ is the fraction of the $Q\overline{Q}$ bound state cross section leading to $J/\psi(\Upsilon)$ production.

Despite its simplicity, the semi-local duality model is capable of describing many features of hadronic $J/\psi$ and $\Upsilon$ productions $[23–26]$. In particular, the shape of $d\sigma/dx_F$ as well as the dependences of the cross sections on the beam energy and the incident-particle type, which are very sensitive to the relative contributions of $gg$ fusion and $q\overline{q}$ annihilation, are well reproduced. The success of the semi-local duality model suggests that it gives a reliable description for the relative importance of these two processes.

Figure 1 shows the $d\sigma/dx_F$ data $[26,27]$ for $J/\psi$ and $\Upsilon$ production using an 800 GeV proton beam. Results of the semi-local duality model calculations using Eq. (8) are shown as the solid curves. The quark masses $m_c$ and $m_b$ were set at 1.5 GeV and 4.5 GeV, respectively, in the calculation. The recent structure function set, DO1.1 $[28]$, was used. The shapes of the differential cross sections are well described by the calculations, and $F$ is determined to be 0.17 and 0.034, respectively, for $J/\psi$ and $\Upsilon$ production.

The contributions from $gg$ fusion and $q\overline{q}$ annihilation to the $J/\psi$ and $\Upsilon$ production cross sections are shown as the dashed and dotted curves, respectively, in Figure 1. For $J/\psi$ production at this beam energy, $gg$ fusion is the dominant process. However, at $x_F > 0.6$, $q\overline{q}$ annihilation process starts to dominate. This reflects the fact that the gluon distribution drops more rapidly at large $x$ than does the quark distribution. For $\Upsilon$ production, Figure 1 shows that $q\overline{q}$ annihilation contributes $\sim 35\%$ of the cross sections near $x_F = 0$, and it is the dominant contribution at large $x_F$. Since $\Upsilon$ is roughly three times more massive than $J/\psi$, production of $\Upsilon$ is more sensitive to structure functions at large $x$, where gluon ceases to dominate the parton densities. This accounts for the relative importance of $q\overline{q}$ annihilation for $\Upsilon$ production.

For $J/\psi$ and $\Upsilon$ production in $p – p$ interactions, the cross section from $u\overline{u}$ and $d\overline{d}$ annihilation, $\sigma(p + p)$, is proportional to
For \( p - d \) interactions, the corresponding cross section, \( \sigma(p + d) \), is

\[
\sigma(p + d) = 2 \sigma(p + p)
\]

Expression (10) now becomes

\[
u_p(x_1)(\bar{u}_p(x_2) + \bar{d}_p(x_2)) + 
\bar{u}_p(x_1)(u_p(x_2) + d_p(x_2))
\]

\[
+ d_p(x_1)(\bar{d}_p(x_2) + \bar{u}_p(x_2)) + 
\bar{d}_p(x_1)(d_p(x_2) + u_p(x_2))
\]

In Eq.(10) the deuteron parton distributions are taken as the sum of the proton (\( p \)) and neutron (\( n \)) distributions. Charge symmetry requires \( u_p(x) = d_n(x), \bar{u}_p(x) = \bar{d}_n(x), \) etc. For a flavor-symmetric sea, \( \bar{u}_p = \bar{d}_p \), Eqs. (9) and (11) give \( \sigma(p + d) = 2\sigma(p + p) \). This relation is also valid for contributions from the \( s\bar{s} \) annihilation and \( gg \) fusion. Therefore, the ratio \( R(x_F) \), defined as

\[
R(x_F) = 2 \frac{d\sigma/dxF (p + p \rightarrow J/\psi(\Upsilon))}{d\sigma/dxF(p + d \rightarrow J/\psi(\Upsilon))}
\]

would be equal to 1 for all models which assume \( \bar{u}_p = \bar{d}_p \). On the other hand, \( R(x_F) \) could deviate significantly from 1 if \( \bar{u}_p \neq \bar{d}_p \), especially at large \( x_F \) where \( q\bar{q} \) annihilation has a dominant contribution.

Figure 2 shows the predictions of \( R(x_F) \) for \( J/\psi \) and \( \Upsilon \) production with 800 GeV proton beam. Five different structure function sets have been used in the calculations. The solid curves correspond to the \( \bar{u}/\bar{d} \) symmetric DO1.1 structure functions. As discussed earlier, \( R(x_F) \) is identically one in this case. The dashed and dotted curves are results for the \( \bar{u}/\bar{d} \) asymmetric structure function sets MRSD-\( t \) and CTEQ2pM, respectively. These two structure function sets were obtained from recent global fits to Drell-Yan and DIS data including the NMC result \([1,3,29]\). Finally, the calculations using the parameterization of \( \bar{d}(x) - \bar{u}(x) \) given by Ellis and Stirling \([3]\) and Eichten et al. \([13]\) are also shown in Figure 2. The parameterizations for \( \bar{d}(x) - \bar{u}(x) \) were given at a fixed value of \( Q^2 \) at 4 GeV\(^2\). The \( Q^2 \)-dependence was taken into account in the calculation by using the Altarelli-Parisi evolution equation for flavor non-singlet structure functions \([3]\).

Figure 2 shows that the measurement of \( R(x_F) \) for \( \Upsilon \) production at 800 GeV provides a sensitive test of models which have different descriptions on the \( \bar{u}/\bar{d} \) symmetry in the proton. In comparison, \( J/\psi \) production is much less sensitive to the sea quark distributions
due to the dominance of $gg$ fusion at this energy. However, at lower beam energies, $J/\psi$ production is more sensitive to the sea quark distributions as it probes a larger $x$ region where $q\bar{q}$ annihilation starts to be important. This is illustrated in Figure 3 which shows the predictions of $R(x_F)$ for $J/\psi$ production using 450 GeV proton beam. The recent result from NA51 \cite{19} is also compared with the predictions. While the predictions are consistent with the data, it is important to extend the measurements to larger $x_F$ values. A measurement of $R(x_F)$ for $J/\psi$ production at even lower beam energies would also be of interest.

It should be mentioned that a more elaborate scheme for calculating hadronic $J/\Psi$ and $\Upsilon$ production, the so-called color-singlet model, has also been proposed \cite{31,32}. This model includes relevant $gg$, $gq$, $g\bar{q}$, and $q\bar{q}$ processes up to order of $\alpha_s^3$, and is capable of predicting the absolute production cross sections. It would be very interesting to compare the predictions of the semi-local duality model and the color-singlet model with the experimental data.

In conclusion, proton-induced $J/\psi$ and $\Upsilon$ production offers an independent means to examine the possible $\bar{u}/\bar{d}$ asymmetry in the proton. Measurement of the cross section ratios on hydrogen and deuterium targets in the forward $x_F$ region would provide a sensitive test of various theoretical models on the sea quark distributions of the proton.
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FIG. 1. $J/\psi$ and $\Upsilon$ production cross sections in $p + Cu$ interactions from References [26], [27]. The solid curves are calculations using the semi-local duality model (Eq.(8)) and DO1.1 structure functions [28]. The contributions from the $gg$ and $q\bar{q}$ annihilation processes are shown as dashed and dotted curves respectively.
FIG. 2. Predictions of $R(x_F)$ for $J/\psi$ and $\Upsilon$ production at 800 GeV using various structure function sets in the semi-local duality model.
FIG. 3. Predictions of $R(x_F)$ for $J/\psi$ production at 450 GeV using various structure function sets in the semi-local duality model. The data from NA51 [19] is also shown.