Probing $u/d$ Asymmetry in the Proton via Quarkonium and $W/Z$ Production

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The experimental and theoretical status of the flavor dependence of the sea quark distributions in the proton is summarized. Sensitivities of \( J/\psi, \chi, \) and \( W/Z \) production to the \( \bar{u}/\bar{d} \) asymmetry are then discussed.

The subject of parton distribution in the nucleons and nuclei has been actively studied for the past two decades. Despite many advances, the sea quark contents in the nucleon are still rather poorly known. In particular, the flavor dependence of the sea quarks in the proton are not well determined. It was assumed by many authors that the \( \bar{u} \) and \( \bar{d} \) sea quark distributions are identical in the proton. It came as a surprise when the NMC collaboration reported\(^1\) a measurement of the Gottfried Sum, showing evidence that \( \bar{u} \neq \bar{d} \) in the proton. In this note, we first summarize the experimental and theoretical status on this subject, and we then discuss how several ongoing and possible future experiments can help to determine the \( \bar{u}/\bar{d} \) ratios in the proton accurately.

The Gottfried Sum is defined as \( I_G(x_1 \to x_2) = \int_{x_1}^{x_2} [F_2^u(x) - F_2^d(x)]/x dx \). Assuming isospin symmetry in the nucleons and \( \bar{u} = \bar{d} \) in the proton, it can be shown straightforwardly that \( I_G(0 \to 1) = 1/3 \), called the Gottfried Sum Rule (GSR).\(^2\) Early SLAC data\(^3\) gave \( I_G(0.02 \to 0.8) = 0.20 \pm 0.04 \), indicating that GSR could be violated. Indeed, these data had prompted Field and Feynman\(^4\) to suggest that Pauli-blocking effect causes suppression of the gluon \( \to u\bar{u} \) process relative to the gluon \( \to d\bar{d} \) process, hence \( \bar{d} > \bar{u} \) in the proton. The NMC collaboration\(^1\) extended the measurement of \( I_G \) to the small \( x \) region. By extrapolating the experimental result \( I_G(0.004 \to 0.8) = 0.221 \pm 0.008 \pm 0.019 \) to the unobserved \( x \) region, NMC obtained \( I_G(0 \to 1) = 0.235 \pm 0.026 \), significantly lower than the value of 1/3 given by GSR.

Many explanations have been proposed for the apparent violation of GSR. Martin et al.\(^5\) suggested that an unusually large contribution to the Gottfried Sum can come from \( x < 0.004 \) such that GSR is not violated. The MRS parameterization gives \( I_G(0 \to 0.004) = 0.10 \) and \( F_2^u/F_2^d < 1 \) as \( x \to 0 \). It is interesting that recent E665 results\(^6\) indeed show that \( F_2^u/F_2^d < 1 \) over the wide range of \( 10^{-6} \leq x \leq 0.3 \). Unfortunately, the \( Q^2 \) values are very small in E665. It would be very desirable to measure \( F_2^u/F_2^d \) at small \( x \) and large \( Q^2 \), perhaps at the HERA collider.

Another interesting explanation was offered by Ma,\(^7\) who pointed out that the charge-symmetry-breaking (CSB) effect could contribute to the apparent violation of GSR. However, an 8% CSB effect, integrated over the entire \( x \) region, is required. This large amount of CSB is inconsistent with the smaller CSB effects observed in other processes. Nevertheless, it is plausible that CSB could contribute partially to the violation of GSR. Recently, Londergan et al.\(^8,9\) also predicted a surprisingly large CSB effect, up to \( \sim 10\% \) at \( x \sim 0.7 \), for the proton valence quark distributions. It would be very interesting to identify the CSB effects at the new level. Several experiments to look for such effects have been suggested.\(^7,8\)
Many authors consider the NMC result as evidence for an asymmetric $\bar{u}, \bar{d}$ distributions in the proton. Using the NMC result for $I_G$ and assuming no CSB effect, one obtains $\int_0^1 \bar{d}(x) - \bar{u}(x)\,dx = 0.14 \pm 0.02$, showing an excess of $\bar{d}$ over $\bar{u}$ in the proton. An interesting interpretation of this result is given by Levelt et al., who define $T = \int_0^1 \bar{u}(x) - d(x)\,dx$ and $\bar{T} = \int_0^1 \bar{d}(x) - \bar{u}(x)\,dx$. One can regard $T/2$ and $\bar{T}/2$ as the proton isospin carried by the quarks and antiquarks, respectively. The NMC result implies $T = 0.86 \pm 0.02$ and $\bar{T} = 0.14 \pm 0.02$; hence suggesting that $-14\%$ of the proton isospin is carried by antiquarks, a situation reminiscent of the proton spin crisis.

What are the mechanisms that would lead to $\bar{d} > \bar{u}$ in the proton? As mentioned earlier, the Pauli-blocking effect favors $\bar{d}$ over $\bar{u}$. Unfortunately, it is difficult to make quantitative calculations. Another mechanism, advocated by many authors, invokes the pion cloud in the proton. In this so-called 'Sullivan process,' the $\pi^+$ in $p \to n + \pi^+$ would contribute to an excess of $\bar{d}$. Detailed calculations taking into account both the $p \to n + \pi^+$ and the $p \to \Delta^{++} + \pi^-$ processes show that $\sim 50\%$ of the observed GSR violation is accounted for. Using a Generalized Sullivan process, which also contains the $N \to K + Y$ processes, Hwang and Speth were able to explain the NMC data well.

It has been proposed that the Drell-Yan process provides an independent and sensitive test of the possible $\bar{u}/\bar{d}$ asymmetry in the proton. In fact, the E772 Drell-Yan data obtained with tungsten and isoscalar targets have been compared with predictions from various models. More recently, the NA51 experiment reported $2\sigma_{DY}(p+p)/\sigma_{DY}(p+d) = 0.91 \pm 0.02 \pm 0.02$ measured at 450 GeV near $x_F = 0$ and $x = 0.18$, showing a large asymmetry of $\bar{u}/\bar{d} = 0.51 \pm 0.04 \pm 0.05$ in the proton. The E866 experiment at Fermilab is designed to measured the ratio $2\sigma_{DY}(p+p)/\sigma_{DY}(p+d)$ over a wide $x$ range ($0.05 < x < 0.3$) at 800 GeV and it should provide a definitive test for the various models.

In addition to the DIS and the Drell-Yan processes, $J/\psi$ and $\Upsilon$ production could also be sensitive to the sea-quark distributions in the nucleon. Using the semi-local duality model and the lowest-order QCD cross sections for the $q\bar{q}$ annihilation and the $gg$ fusion processes, the sensitivity of the proton-induced $J/\psi$ and $\Upsilon$ production to the possible $\bar{u}/\bar{d}$ asymmetry has been studied. The ratio $R(x_F)$, defined as

$$R(x_F) = 2 \frac{d\sigma/dx_F(p+p \to J/\psi(\Upsilon))}{d\sigma/dx_F(p+d \to J/\psi(\Upsilon))},$$

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

Figure 1 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, and $R(x_F)$ is identically one in this case. Figure 1 shows that the measurement of $R(x_F)$ for $\Upsilon$ production at 800 GeV provides a sensitive test of models that predict different $\bar{u}/\bar{d}$ symmetry in the proton. In comparison, $J/\psi$ production is 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 the $q\bar{q}$ annihilation starts to be important.

The opportunity to study $p+p$ and $p+A$ collisions at the future heavy ion collider, RHIC, suggests yet another process, namely the production of $W$ and $Z$ bosons, which is sensitive to
the $u/d$ asymmetry. An interesting quantity to be considered is the ratio of the differential cross sections for $W^+$ and $W^-$ production. If one ignores the much smaller contribution from the strange quarks, this ratio can be written as

\[
R(x_F) \equiv \frac{\frac{d\sigma}{dx_F}(W^+)}{\frac{d\sigma}{dx_F}(W^-)} = \frac{u(x_1)d(x_2) + u(x_1)\bar{d}(x_2)}{u(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}.
\]

Figure 2(a) shows the predictions of $R(x_F)$ for $p+p$ collisions at $\sqrt{s} = 500$ GeV. Five different structure function sets have been used in the calculations. It is clear that the measurement of $R(x_F)$ for $W$ production in $p+p$ collisions at RHIC could provide a sensitive test of various models. In contrast, $R(x_F)$ for $p+\bar{p}$ collisions is only sensitive to the valence quark distribution and not sensitive to the $u/d$ asymmetry, as shown in Fig. 2(b). Two other observables are also sensitive to the $u/d$ asymmetry. One is the ratio of $W^+$ production cross sections for $p+p$ and $p+d$ collisions. The other is the ratio of $Z^0$ production cross sections in $p+p$ and $p+d$ collisions. Predictions of these ratios using various models have been shown in Ref. 16. Both of these ratios could be studied at RHIC.

References

Fig. 2. Predictions of $R(x_F)$ using various structure functions for (a) $p+p$ collisions, and (b) $p+\bar{p}$ collisions at $S^{1/2} = 500$ GeV.