Flavor Asymmetry $\bar{u} - \bar{d}$ in the Nucleon

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Abstract

We give a brief summary of the Gottfried sum rule and a flavor asymmetric distribution $\bar{u} - \bar{d}$ in the nucleon. First, experimental history of the sum-rule studies is discussed. Second, future prospects for studying the asymmetry at Fermilab and RHIC are discussed. We also comment on possible nuclear modification.

1. Introduction

Unpolarized parton distributions in the nucleon are now well understood by analyzing abundant high-energy experimental data. However, light antiquark distributions had been considered flavor symmetric until rather recently. It is because $u$ and $d$ quark masses are very small compared with typical $\sqrt{Q^2}$ in deep inelastic processes. Therefore, equal mounts of $u\bar{u}$ and $d\bar{d}$ pairs are produced perturbatively through gluon splitting. Although it was somewhat suggested in the SLAC data in 1970's, the NMC conclusion of the $\bar{u}/\bar{d}$ asymmetry in 1991 was surprising.

As far as theory is concerned, there are several proposed models for explaining the NMC result. Those include Pauli-blocking mechanism, mesonic clouds, diquark model, and so on. These ideas are not discussed in this paper due to lack of space. Interested reader may read a summary paper in Ref. [1].

In spite of the NMC suggestion, it is still not obvious whether the Gottfried sum rule is in fact violated due to a possible small-$x$ contribution. Therefore, independent experimental information is necessary for finding an accurate $\bar{u} - \bar{d}$ distribution. The NA51 Drell-Yan experiment in 1994 suggests a large flavor asymmetry, which is consistent with the NMC finding. Right now, the Drell-Yan experiment is in progress at the Fermilab, and we expect to have much detailed results in the near future. On the other hand, the other hadron collider RHIC should also be able to provide information on the asymmetry.

In this paper, we first discuss experimental history of the Gottfried sum rule and its relation to the flavor asymmetry $\bar{u} - \bar{d}$ in section 2. Then, Drell-Yan and $W$ production processes are explained in sections 3 and 4 for finding the asymmetry at Fermilab or RHIC.
2. Gottfried sum rule and flavor asymmetry $\bar{u} - \bar{d}$

The Gottfried sum rule is associated with the difference of proton and neutron $F_2$ structure functions measured in unpolarized electron or muon scattering. Because there is no fixed neutron target, the deuteron is usually used for obtaining the neutron $F_2$ by subtracting out the proton part. Using the parton-model expression:

$$F_2(x, Q^2) = \sum_i e_i^2 x [q_i(x, Q^2) + \bar{q}_i(x, Q^2)],$$

the baryon-number relation

$$\int_0^1 dx (u_v - d_v) = 1,$$

and isospin symmetry, we obtain

$$\int_0^1 \frac{dx}{x} [F_2^p(x, Q^2) - F_2^n(x, Q^2)] = \frac{1}{3} + \frac{2}{3} \int_0^1 dx [\bar{u}(x, Q^2) - \bar{d}(x, Q^2)].$$

(1)

If the sea is flavor symmetric ($\bar{u} = \bar{d}$), the second term vanishes and it becomes the Gottfried sum rule

$$\int_0^1 \frac{dx}{x} [F_2^p(x, Q^2) - F_2^n(x, Q^2)] = \frac{1}{3}.$$  

(2)

As it is obvious in the above derivation, there is a serious assumption of the flavor symmetry in light-antiquark distributions. Therefore, it is not a rigorous sum rule. It is nevertheless interesting to test the sum rule because its violation could suggest flavor asymmetric sea in the nucleon.

The first test of the sum rule is studied at SLAC in the 1970’s. According to a SLAC paper in 1975, the integral is $I_G(0.02, 0.82) = 0.200 \pm 0.040$, where we use the notation $I_G(x_{\text{min}}, x_{\text{max}})$ for the Gottfried integral with minimum and maximum of the integral. It is interesting to find a significantly smaller value than the Gottfried sum 1/3. It is, however, not conclusive enough to state that the sum rule is violated due to a possible large contribution from the smaller $x$ region. In Fig. 1, we show the SLAC result and subsequent results by the EMC [$I_G(0, 1) = 0.235^{+0.110}_{-0.099}$], the BCDMS [$I_G(0.06, 0.8) = 0.197 \pm 0.006(\text{stat.}) \pm 0.036(\text{syst.})$], and the NMC [$I_G(0, 1) = 0.240 \pm 0.016$ in 1991 and $I_G(0, 1) = 0.235 \pm 0.026$ in 1994]. The SLAC and BCDMS data are shown by open circles because small $x$ contribution is not estimated. The NMC 1991 result is the first clear indication of the sum-rule violation because of the small error. From Eq. (1), the NMC value $I_G=0.235$ could be explained by the flavor asymmetry, namely a $\bar{d}$ excess over $\bar{u}$. Next, we discuss other processes for testing the NMC $\bar{u}/\bar{d}$ asymmetry.
3. Drell-Yan process

The NMC data are not enough for obtaining accurate $\bar{u}$ and $\bar{d}$ distributions. As one of the other methods for studying the flavor asymmetry, Drell-Yan process has been studied. The Drell-Yan is a lepton-pair production process in hadron-hadron collisions $A + B \rightarrow \ell^+ \ell^- X$. In the parton model, it is described by quark-antiquark annihilation processes $q + \bar{q} \rightarrow \ell^+ \ell^-$. The cross section is given by

$$\sigma_{DY} \propto \sum_i e_i^2 q_i^A(x_1,Q^2)\bar{q}_i^B(x_2,Q^2) + \bar{q}_i^A(x_1,Q^2)q_i^B(x_2,Q^2),$$

where $Q^2$ is the dimuon mass squared $Q^2 = m_{\mu \mu}^2$. Drell-Yan p-n asymmetry at large $x_F$ is given by

$$A_{DY} \equiv \frac{\sigma^{pp} - \sigma^{pn}}{\sigma^{pp} + \sigma^{pn}} \approx \frac{[4u(x_1) - d(x_1)][\bar{u}(x_2) - \bar{d}(x_2)]}{[4u(x_1) + d(x_1)][\bar{u}(x_2) + \bar{d}(x_2)]}.$$  \hspace{1cm} (3)

It is directly proportional to the $\bar{u} - \bar{d}$ distribution.

There is a CERN-NA51 result: $\bar{u}/\bar{d} = 0.51 \pm 0.04{\text{(stat.)}} \pm 0.05{\text{(syst.)}}$ at $x=0.18$, which is a clear indication of the $\bar{u}/\bar{d}$ asymmetry. There are also Fermilab Drell-Yan data by E288 and E772; however, the results are not conclusive enough for finding the asymmetry. For example, the E772 data ($x_F > 0.1$) are shown in Fig. 2 together with theoretical curves of flavor asymmetry. Because the ratio is given by $\sigma_A/\sigma_{IS} \approx 1 + [(N-Z)/A][\bar{d}(x) - \bar{u}(x)]/[\bar{d}(x) + \bar{u}(x)]$, the deviation from unity indicates a $\bar{u}/\bar{d}$ asymmetry. It is not obvious from the figure whether or not light antiquarks are flavor symmetric. However, the experimental analysis are currently in progress at the Fermilab, so we expect have new accurate information in the near future.

It should be noted that the E772 data are taken by nuclear targets. The tungsten is a heavy nucleus with neutron excess. Strictly speaking, they cannot be compared with the NMC data due to possible nuclear modification. Nuclear interactions may change the $\bar{u} - \bar{d}$ distribution. The modification is estimated in a parton-recombination model, which is one of the ideas for explaining behavior of parton distributions in the shadowing region. Because of the neutron excess in the tungsten nucleus, the $d\bar{d}$ recombination could
occur more frequently than the $u\bar{u}$. It means that a finite $u\bar{d}$ asymmetry is produced even if it is symmetric ($\bar{u} = \bar{d}$) in the nucleon. We show the $\bar{u} - \bar{d}$ distributions, which are created by the recombinations in Fig. 3. The detailed calculations are explained in Ref. [3]. Depending on the flavor distribution in the nucleon, the results show interesting nuclear modification effects. They are calculated at $Q^2=4 \text{ GeV}^2$; however, the modification should be larger at smaller $Q^2$ because of higher-twist nature. Therefore, the nuclear effects are typically a few or several % in comparison with the $\bar{u} - \bar{d}$ distribution which is suggested by the NMC data. It is important to test the nuclear modification by the Drell-Yan experiments for nuclear targets.

4. W production

W production is investigated for measuring $\bar{u} - \bar{d}$ by several people [1]. Here, we discuss this topic based on Peng-Jansen studies [4]. The dominant subprocess of producing $W^+$ is $u + \bar{d} \rightarrow W^+$, so that the $\bar{d}$ distribution could be extracted from $W^+$ production data. On the other hand, the dominant process of $W^-$ production is $d + \bar{u} \rightarrow W^-$, and $\bar{u}$ information can be obtained instead of $\bar{d}$. This difference makes it possible to find the asymmetric distribution $\bar{u} - \bar{d}$. The $W^+$ production cross section is given by

$$\frac{d\sigma_{p+p\rightarrow W^+}}{dx_F} \propto \cos^2 \theta_c [u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)]$$

$$+ \sin^2 \theta_c [u(x_1)\bar{s}(x_2) + \bar{s}(x_1)u(x_2)].$$

Because the Cabbibo angle $\theta_c$ is small, the $\sin^2 \theta_c$ terms are neglected for simplicity in the following discussions. Then, the processes of producing $W^+$ are $u(x_1) + \bar{d}(x_2) \rightarrow W^+$ and $u(x_2) + \bar{d}(x_1) \rightarrow W^+$. The $W^-$ cross section is calculated in the similar way, and we obtain the $W^\pm$ production ratio

$$R_{p+p}(x_F) \equiv \frac{d\sigma_{p+p\rightarrow W^+}/dx_F}{d\sigma_{p+p\rightarrow W^-}/dx_F} = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + \bar{d}(x_1)\bar{u}(x_2)}. \quad (5)$$

At large $x_F$ (large $x_1$), the antiquark distribution $\bar{q}(x_1)$ is very small, so that the above equation becomes $R_{p+p}(x_F \gg 0) \approx [u(x_1)/d(x_1)][\bar{d}(x_2)/\bar{u}(x_2)]$, which is directly proportional to the $\bar{d}/\bar{u}$ ratio. On the other hand, we have $R_{p+p}(x_F \gg 0) \approx [u(x_1)/d(x_1)][\bar{d}(x_2)/u(x_2)]$ in the $p + \bar{p}$ reaction case. In the $x_F = 0$ region, even though the $p + p$ ratio is still sensitive to the flavor asymmetry: $R_{p+p}(x_F = 0) = [u(x)/d(x)][\bar{d}(x)/\bar{u}(x)]$, the $p + \bar{p}$ ratio is independent: $R_{p+p}(x_F = 0) = 1$. Therefore, the $p + \bar{p}$ reaction is not a good way for finding the flavor asymmetry. This situation is clearly shown in Fig. 4, where the $W^\pm$ production ratio is calculated in the $p + p$ and $p + \bar{p}$ cases.
The $W^{\pm}$ ratios in the $p + p$ and $p + \bar{p}$ reactions are evaluated at $\sqrt{s}=500$ GeV by using various parametrizations for the parton distributions [4]. The distributions are evolved to the scale $Q^2 = M_W^2$. The figures a) and b) show the $p + p$ and $p + \bar{p}$ results respectively. The dashed curve indicates results of using the flavor symmetric ($\bar{u} = \bar{d}$) DO1.1 distributions. Others are the results for flavor asymmetric distributions (MRSD0−′, CTEQ2pM, ES, EHQ). As we expected, the $p + p$ reaction is sensitive to the light antiquark flavor asymmetry not only in the large $x_F$ region but also in the $x_F \approx 0$ region. On the other hand, the $p + \bar{p}$ reaction is almost insensitive to the asymmetry. The dependence appears only in the very small $x_F$ region.

There are other possibilities such as Z and quarkonium production processes for finding the $\bar{u} - \bar{d}$ distribution. These topics as well as theoretical ideas are summarized in Ref. [1]. The flavor symmetry is an interesting topic for future investigations. It is currently being studied at Fermilab and should be investigated at RHIC. Furthermore, the asymmetry in polarized parton distributions ($\Delta \bar{u}/\Delta \bar{d}$) is an unexplored subject, which will be studied for example at RHIC-SPIN.

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