

Flavor distributions in the nucleons: SU(2) sea asymmetry or isospin symmetry breaking?

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(Received 27 August 1992)

The Gottfried sum-rule violation reported by the New Muon Collaboration was interpreted as an indication for a flavor asymmetry of the sea quark in the nucleon. We investigate the alternative possibility that isospin symmetry between the proton and the neutron is breaking. We examine systematically the consequences of this possibility for several processes, namely, neutrino deep inelastic scattering, the charged pion Drell-Yan process, the proton Drell-Yan process, and semi-inclusive deep inelastic scattering, and conclude that a decision between the two alternative explanations is possible.

PACS number(s): 14.20.Dh, 13.15.-f, 13.60.Hb, 13.85.Qk

I. INTRODUCTION

Recently, the measurement of the Gottfried sum [1] by the New Muon Collaboration (NMC) [2] has inspired a number of investigations on the sea-quark flavor distributions of nucleons [3–21]. The Gottfried sum is defined, in terms of the proton and neutron structure functions $F_2(x)$, as $S_G = \int_0^1 [F_2^p(x) - F_2^n(x)] dx/x$, which, when expressed in terms of quark momentum distributions $q_i^N(x)$ in the nucleon N , reads

$$S_G = \int_0^1 \sum_i e_i^2 [q_i^p(x) + \bar{q}_i^p(x) - q_i^n(x) - \bar{q}_i^n(x)] dx, \quad (1.1)$$

where e_i is the charge of a quark of flavor i . Using flavor conservation, isospin symmetry between the proton and the neutron, and further the flavor distribution symmetry in the sea, one arrives at the Gottfried sum rule (GSR) $S_G = 1/3$. In the NMC experiment, the value of S_G was determined from $F_2^p - F_2^n$ expressed as

$$F_2^p - F_2^n = 2F_2^D(1 - F_2^n/F_2^p)/(1 + F_2^n/F_2^p), \quad (1.2)$$

where the ratio $F_2^n/F_2^p = 2F_2^D/F_2^p - 1$ was determined from the deuteron/proton cross-section ratio measured in the experiment. The data cover the kinematic range of $x = 0.004 - 0.8$ for $Q^2 = 4 \text{ GeV}^2$. Assuming a smooth extrapolation of the data F_2^n/F_2^p from $x = 0.8$ to 1, and adopting a Regge behavior ax^b for $F_2^p - F_2^n$, a flavor nonsinglet, in the region $x = 0.004 - 0.15$ and then extrapolating it to $x = 0$, the NMC reported the value for the Gottfried sum

$$S_G = 0.240 \pm 0.016, \quad (1.3)$$

which is significantly below the simple quark-parton-model result of $1/3$.

Several different effects have been proposed as the source for this discrepancy between the NMC data and the GSR. In several early works [3–6] the NMC data were claimed as evidence for a flavor distribution asymmetry in the sea of nucleons, i.e., an excess of $d\bar{d}$ over $u\bar{u}$ pairs in the proton [3–6]. This suppression of $u\bar{u}$ pairs could be due to the Pauli exclusive principle and the excess of a u valence quark in the proton [22, 9]. A flavor-SU(2) asymmetry in the sea can also be attributed to the pionic contribution as an excess of $p \rightarrow n + \pi^+$ over $p \rightarrow \Delta^{++} + \pi^-$ (or π^+ over π^-) [4–8], or from a more microscopic point of view to the excess of $u \rightarrow d + \pi^+$ over $u \rightarrow u + \pi^0$ and $d \rightarrow u + \pi^-$ over $d \rightarrow d + \pi^0$ [10, 11]. Other possibilities are that the smaller NMC result for the GSR is due to the unjustified $x \rightarrow 0$ extrapolation of the available data [12] or due to a small admixture of vector diquarks in a particular quark-diquark model of the nucleon [13]. More recently, it has been observed [14] that the violation of the GSR could also be due to isospin symmetry breaking between the proton and the neutron, while the sea flavor distribution symmetry of nucleons is preserved. According to this explanation there are more sea quarks in the neutron than in the proton. Nuclear effects have also been examined [15–18], and it has been suggested that, e.g., the mesonic exchanges in the deuteron [15] could account for the difference between the NMC data and the GSR, although nuclear shadowing corrections may lead to smaller values of S_G than reported by the NMC [17, 18].

In this paper we discuss the possibility of explicit isospin symmetry breaking between the proton and the neutron, i.e., $u^p(x) \neq d^n(x)$, etc. For simplicity we shall always assume sea flavor symmetry [$\bar{u}^N(x) = \bar{d}^N(x)$] although both effects could occur simultaneously. We shall review the various experiments proposed to determine the origin of the small NMC data and analyze what results would be expected for our assumptions. In the paper by Kumano and Londergan [18] it was argued that a combination of neutrino structure functions of the pro-

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ton and deuteron, or an expression of the relative Drell-Yan cross sections for charged pions scattering from nuclear targets, are sensitive to the quantity $\bar{d} - \bar{u}$. Ellis and Stirling [19] suggested comparing $pp \rightarrow l^+l^-X$ and $pn \rightarrow l^+l^-X$ to distinguish between the SU(2) asymmetry in the sea and a non-Regge behavior at small x . Levelt, Mulders, and Schreiber [20] discussed the possible measurement of the asymmetry in the sea-quark distribution using semi-inclusive leptonproduction of charged pions and, more generally, by charged hadrons, to check for flavor asymmetries. These above processes were discussed before the observation [14] that isospin symmetry breaking between the proton and the neutron could be an alternative source for the GSR violation. The purpose of this paper is to examine the influences from p - n isospin symmetry breaking for the above processes. It is necessary to point out that the nuclear mesonic exchange explanation [15] also suggested an excess of mesonic contributions over the isospin symmetric p - n in deuteron and thus should give the same results as isospin symmetry breaking if free neutrons are not involved in the measurements.

II. DEEP INELASTIC NEUTRINO SCATTERING

The possibility of distinguishing between an SU(2) sea asymmetry and p - n isospin symmetry breaking through deep inelastic neutrino and antineutrino scattering on protons and deuterons has been discussed in Ref. [14]. If the SU(2) sea is asymmetric the violation of the GSR indicates an excess of $d\bar{d}$ over $u\bar{u}$; i.e.,

$$\int_0^1 [\bar{u}(x) - \bar{d}(x)] = -0.140 \pm 0.024, \quad (2.1)$$

whereas for p - n isospin symmetry breaking the violation of GSR is due to an excess of sea quarks in neutrons over those in protons while preserving the SU(2) symmetry in the sea of nucleons; i.e.,

$$\int_0^1 [\bar{q}^p(x) - \bar{q}^n(x)] = -0.084 \pm 0.014. \quad (2.2)$$

Both explanations are fitted to the observed S_G but may give very different values for some linear combinations of neutrino structure functions from protons and deuterons. In Ref. [14] a new sum, defined by

$$S = \int_0^1 [(F_2^{\nu p} + F_2^{\bar{\nu} p}) - \frac{1}{2}(F_2^{\nu D} + F_2^{\bar{\nu} D})] dx, \quad (2.3)$$

was suggested. This new sum is zero for an asymmetric sea explanation and $4 \int_0^1 [\bar{q}^p(x) - \bar{q}^n(x)] = -0.336 \pm 0.058$ for p - n symmetry breaking. Some other combinations, such as those indicated in Ref. [14], may also be chosen to distinguish between the two explanations.

The linear combination of neutrino structure functions from protons and deuterons,

$$\frac{1}{2}[F_2^{\nu D}(x) - xF_3^{\nu D}(x)] - [F_2^{\nu p}(x) - xF_3^{\nu p}(x)], \quad (2.4)$$

which was proposed by Kumano and Londergan [18] to measure the difference $\bar{u} - \bar{d}$, should be

$$2x[\bar{d}(x) - \bar{u}(x)] \quad (2.5)$$

in the case of SU(2) asymmetry in the sea. This combination, when expressed in terms of quark momentum distributions, should read

$$2x[\bar{u}^n(x) - \bar{u}^p(x)], \quad (2.6)$$

while it gives

$$2x[\bar{q}^n(x) - \bar{q}^p(x)] \quad (2.7)$$

in the case of isospin symmetry breaking between the proton and the neutron. The two cases give different values for Eq. (2.4). From Eqs. (2.1) and (2.2), one can see that the prediction for Eq. (2.4) is less for the n - p isospin symmetry breaking than for the SU(2) sea asymmetry.

III. DRELL-YAN PROCESSES

A. Drell-Yan processes using charged pion from nuclear targets

Also in Ref. [18] the quantity $\bar{d}(x) - \bar{u}(x)$ was suggested to be measured by Drell-Yan processes $\pi^\pm A \rightarrow l^+l^-X$ initiated by charged pion scattering from nuclear targets. For large x_π , say $x_\pi > 0.4$, the cross section per nucleon for π^+ and π^- scattering from nuclear targets will be proportional to

$$\begin{aligned} \tilde{\sigma}(\pi^+ A) = V_\pi [& \frac{1}{2}(d^n + 4\bar{u}^n + d^p + 4\bar{u}^p) \\ & + \varepsilon(d^n + 4\bar{u}^n - d^p - 4\bar{u}^p)], \end{aligned} \quad (3.1)$$

$$\begin{aligned} \tilde{\sigma}(\pi^- A) = V_\pi [& \frac{1}{2}(4u^n + \bar{d}^n + 4u^p + \bar{d}^p) \\ & + \varepsilon(4u^n + \bar{d}^n - 4u^p - \bar{d}^p)], \end{aligned}$$

where $\varepsilon \equiv N/A - 1/2$ is the neutron excess of the target with A nucleons and V_π is the valence distribution of the pion. Thus one can define the ratio

$$R_{\text{sea}} = \frac{4[\tilde{\sigma}(\pi^+ A_1) - \tilde{\sigma}(\pi^+ A_0)] + \tilde{\sigma}(\pi^- A_1) - \tilde{\sigma}(\pi^- A_0)}{\tilde{\sigma}(\pi^+ A_0) - \tilde{\sigma}(\pi^- A_0)}. \quad (3.2)$$

In the case of an asymmetric SU(2) sea, one assumes p - n isospin symmetry: i.e.,

$$\begin{aligned} u = u^p \leftrightarrow d^n, \quad d = d^p \leftrightarrow u^n, \\ \bar{u} = \bar{u}^p \leftrightarrow \bar{d}^n, \quad \bar{d} = \bar{d}^p \leftrightarrow \bar{u}^n; \end{aligned} \quad (3.3)$$

then one gets

$$R_{\text{sea}} = \frac{10(\varepsilon_1 - \varepsilon_0)(\bar{u} - \bar{d})}{u_V + d_V}. \quad (3.4)$$

In the case of p - n isospin symmetry breaking, we assume that only the valence quarks preserve the isospin symme-

try between the proton and the neutron, while sea quarks do not; then it can be found that

$$R_{\text{sea}} = \frac{50(\varepsilon_1 - \varepsilon_0)(\bar{q}^p - \bar{q}^n)}{3(u_V + d_V)}. \quad (3.5)$$

From Eqs. (2.1) and (2.2) we know the relation

$$\int_0^1 [\bar{q}^p(x) - \bar{q}^n(x)] = \frac{3}{5} \int_0^1 [\bar{u}(x) - \bar{d}(x)] \quad (3.6)$$

between p - n isospin symmetry breaking and an asymmetric SU(2) sea; thus we can reasonably assume

$$[\bar{q}^p(x) - \bar{q}^n(x)] = \frac{3}{5}[\bar{u}(x) - \bar{d}(x)]. \quad (3.7)$$

Substituting this relation into Eq. (3.5) we arrive at Eq. (3.4). Thus the two explanations give approximately the same result for Eq. (3.2) introduced by Kumano and Londergan.

B. Drell-Yan processes by proton scattering

We now turn our attention to the Drell-Yan processes for protons scattered from proton and deuteron targets, which are discussed by Ellis and Stirling [19], and also by Kumano and Londergan [21] recently. The cross section of the process $pN \rightarrow l^+l^-X$ is sensitive to the sea-antiquark distributions:

$$s \frac{d^2 \sigma^{pN}}{d\sqrt{\tau} dy} = \frac{8\pi\alpha^2}{9\sqrt{\tau}} \sum_i e_i^2 q_i^p(x_1, M) \bar{q}_i^N(x_2, M) + [1 \leftrightarrow 2], \quad (3.8)$$

$$A_{\text{DY}} = \frac{(4u_V - d_V)5(\bar{q}^p - \bar{q}^n)/3 + (u_V - d_V)(\bar{q}^p + 8\bar{q}^n)/3}{9(\sigma^{pp} + \sigma^{pn})}. \quad (3.12)$$

Comparing Eq. (3.12) with Eq. (3.11), one can find that the p - n cross-section asymmetry could also change sign in the case of isospin symmetry breaking between the proton and the neutron. Using Eq. (3.7) and adopting $(4\bar{u} - \bar{d}) \sim (\bar{q}^p + 8\bar{q}^n)/3$, we see that Eq. (3.12) will give approximately the same value as Eq. (3.11). Therefore, the Drell-Yan processes discussed in the literature [18, 19, 21] are not sufficient to distinguish between an asymmetric SU(2) sea and p - n isospin symmetry breaking for charged pion scattering Eq. (3.2) as well as for proton scattering Eq. (3.10).

IV. SEMI-INCLUSIVE DEEP INELASTIC SCATTERING

It has been suggested by Levelt, Mulders, and Schreiber (LMS) [20] that the semi-inclusive leptoproduction of hadrons in deep inelastic electron or muon scattering can be used as a check of SU(2) asymmetry in the proton sea. We will show that the breakdown of p - n isospin symmetry could also contribute to this process and account for the data. According to the quark-parton model considerations [23], the number of hadrons h produced by a scattering off the nucleon N in a given bin of x Bjorken variable and $z = E_h/\nu$ should be, up to a

where $\tau = M^2/s$, $x_1 = \sqrt{\tau}e^\nu$, and $x_2 = \sqrt{\tau}e^{-\nu}$. We ignore, following Ellis and Stirling and Kumano and Londergan, the contributions from strange and charm quarks and retain only the dominant ‘‘valence-sea’’ annihilation terms in the remainder; then we get, at $y = 0$,

$$\sigma^{pp} \equiv s \frac{d^2 \sigma^{pp}}{d\sqrt{\tau} dy} = \frac{8\pi\alpha^2}{9\sqrt{\tau}} \left(\frac{8}{9} u_V^p \bar{u}^p + \frac{2}{9} d_V^p \bar{d}^p \right), \quad (3.9)$$

$$\sigma^{pn} \equiv s \frac{d^2 \sigma^{pn}}{d\sqrt{\tau} dy} = \frac{8\pi\alpha^2}{9\sqrt{\tau}} \left[\frac{4}{9} (u_V^p \bar{u}^n + u_V^n \bar{u}^p) + \frac{1}{9} (d_V^p \bar{d}^n + d_V^n \bar{d}^p) \right].$$

The p - n cross-section asymmetry

$$A_{\text{DY}} = \frac{\sigma^{pp} - \sigma^{pn}}{\sigma^{pp} + \sigma^{pn}} \quad (3.10)$$

discussed by Ellis-Stirling becomes

$$A_{\text{DY}} = \frac{(4u_V - d_V)(\bar{u} - \bar{d}) + (u_V - d_V)(4\bar{u} - \bar{d})}{(4u_V + d_V)(\bar{u} + \bar{d}) + (u_V + d_V)(4\bar{u} + \bar{d})} \quad (3.11)$$

for a SU(2)-asymmetric sea. It was found by Ellis and Stirling that the quantity Eq. (3.11) can change sign for an asymmetric sea, whereas it is positive in the case that the violation of the GSR is due to the unjustified $x \rightarrow 0$ extrapolation of the data. We assume instead that only the valence quarks preserve the isospin symmetry between the proton and the neutron, while sea quarks do not. Thus we find

constant factor,

$$N^{Nh}(x, z) \equiv \sum_i e_i^2 q_i^N(x) D_i^h(z), \quad (4.1)$$

where $q_i^N(x)$ is the distribution function for quarks of flavor i in the nucleon N and D_i^h is the fragmentation function of a quark with flavor i into the hadron h with energy $E_h = z\nu$. Defining

$$Q(z) = \frac{N^{p+} - N^{n+} + N^{p-} - N^{n-}}{N^{p+} - N^{n+} - N^{p-} + N^{n-}}, \quad (4.2)$$

where $N^{N\pm} = \int dx N^{N\pm}(x, z)$ is for \pm charged hadrons, LMS found, assuming p - n isospin symmetry [i.e., Eq. (3.3)],

$$Q(z) = 3S_G \frac{4[D_u^+(z) + D_u^-(z)] - [D_d^+(z) + D_d^-(z)]}{4[D_u^+(z) - D_u^-(z)] - [D_d^+(z) - D_d^-(z)]}, \quad (4.3)$$

which is directly proportional to the outcome of the GSR in inclusive leptoproduction. After some detailed examination of charged pions, kaons, and protons and antiprotons, LMS derived an expression for $Q^{\text{ch}}(z)$, using $D_u^+ = D_u^{\pi^+} + D_u^{K^+} + D_u^p$:

$$zQ^{\text{ch}}(z) = 3S_G z \frac{0.50z^2 + 3.1z + 7.6}{3.2z^2 + 11z + 0.84}. \quad (4.4)$$

They found that the data are consistent with both $S_G = 0.24$ and $S_G = 1/3$.

We now examine the case that the violation of GSR is due to isospin symmetry breaking between the proton and the neutron, while preserving SU(2) symmetry in the sea of nucleons. It can be seen, from Eq. (4.1),

$$N^{p\pm} = \frac{4}{9}u^p D_u^\pm + \frac{4}{9}\bar{u}^p D_{\bar{u}}^\pm + \frac{1}{9}d^p D_d^\pm + \frac{1}{9}\bar{d}^p D_{\bar{d}}^\pm + \frac{1}{9}s^p D_s^\pm + \frac{1}{9}\bar{s}^p D_{\bar{s}}^\pm, \quad (4.5)$$

$$N^{n\pm} = \frac{4}{9}u^n D_u^\pm + \frac{4}{9}\bar{u}^n D_{\bar{u}}^\pm + \frac{1}{9}d^n D_d^\pm + \frac{1}{9}\bar{d}^n D_{\bar{d}}^\pm + \frac{1}{9}s^n D_s^\pm + \frac{1}{9}\bar{s}^n D_{\bar{s}}^\pm.$$

Assuming charge conjugation invariance one has $D_u^\pm = D_{\bar{u}}^\mp$ and $D_d^\pm = D_{\bar{d}}^\mp$. The flavor number conservation requires $u_V = u^p - \bar{u}^p = d^n - \bar{d}^n = 2$ and $d_V = d^p - \bar{d}^p = u^n - \bar{u}^n = 1$; thus, one obtains

$$N^{p+} - N^{n+} = \frac{4}{9}D_u^+(1 - \delta\bar{q}) - \frac{4}{9}D_{\bar{u}}^+\delta\bar{q} - \frac{1}{9}D_d^+(1 + \delta\bar{q}) - \frac{1}{9}D_{\bar{d}}^+\delta\bar{q}, \quad (4.6)$$

$$N^{p-} - N^{n-} = \frac{4}{9}D_u^-(1 - \delta\bar{q}) - \frac{4}{9}D_{\bar{u}}^-\delta\bar{q} - \frac{1}{9}D_d^-(1 + \delta\bar{q}) - \frac{1}{9}D_{\bar{d}}^-\delta\bar{q},$$

from which we get

$$Q(z) = \frac{4[D_u^+(z) + D_{\bar{u}}^+(z)](1 - 2\delta\bar{q}) - [D_d^+(z) + D_{\bar{d}}^+(z)](1 + 2\delta\bar{q})}{4[D_u^+(z) - D_{\bar{u}}^+(z)] - [D_d^+(z) - D_{\bar{d}}^+(z)]}, \quad (4.7)$$

where $\delta\bar{q} = \bar{q}^n - \bar{q}^p$ is the excess of sea quarks in the neutron over those in the proton. It can be seen that Eq. (4.7) is different from Eq. (4.3) unless $S_G = 1/3$ [i.e., $\bar{d} - \bar{u} = 0$ in the SU(2) sea asymmetry explanation and $\delta\bar{q} = \bar{q}^n - \bar{q}^p = 0$ in the p - n isospin symmetry-breaking explanation]. Following the similar analyses of Ref. [20] we find that the expressions $Q^\pi(z)$ and $Q^p(z)$ are the same as for an asymmetric SU(2). However, $Q^K(z)$ is now

$$Q^K(z) = \frac{(D^K + \tilde{D}^K)(\frac{2}{5} + \frac{9}{5}S_G) - \frac{1}{2}\tilde{D}'^K(\frac{8}{5} - \frac{9}{5}S_G)}{D^K - \tilde{D}^K}, \quad (4.8)$$

which is different from Eq. (24) of Ref. [20] unless $S_G = 1/3$. Thus we have, for $D_u^+ = D_u^{\pi+} + D_u^{K+} + D_u^p$,

$$zQ^{\text{ch}}(z) = 3S_G z \frac{0.80z^2 + 3.37z + 7.63}{3.2z^2 + 11z + 0.84} \quad (4.9)$$

for $S_G = 0.24$ in the case of isospin symmetry breaking between the proton and the neutron. Comparing Eq. (4.4) and Eq. (4.9), we see that the expressions for $Q^{\text{ch}}(z)$ are different for the two explanations. In the latter case the result is between the GSR prediction and the prediction for an asymmetric SU(2) sea and thus is also consistent with the data of Ref. [20]. To distinguish between an asymmetric SU(2) sea and p - n isospin symmetry breaking from $Q^{\text{ch}}(z)$, we need data with better accuracy.

V. SUMMARY

We have examined several processes, which have been suggested to check whether the violation of the GSR is due to an asymmetric SU(2) sea, and found that these processes are also sensitive to any excess of sea quarks in the neutron over those in the proton. A linear combination of neutrino structure functions from protons and deuterons [i.e., Eq. (2.4)], and the ratio $Q^{\text{ch}}(z)$ [i.e., Eq. (4.2)] for semi-inclusive lepton production of charged hadrons can distinguish between the two possible explanations of the NMC data, namely, an asymmetric SU(2) sea and p - n isospin symmetry breaking, or combinations of both. The values for the case of p - n isospin symmetry breaking are between those for the GSR and those for the SU(2) sea asymmetry explanation. The quantities R_{sea} [i.e., Eq. (3.2)] in charged pion Drell-Yan processes and A_{DY} [i.e., Eq. (3.10)] in proton Drell-Yan processes give approximately the same values for the two different explanations and thus are difficult to settle the origin of the GSR violation. The specific combination of neutrino and antineutrino scattering data on protons and deuterons proposed in Ref. [14] seems well suited to distinguish between the two alternative explanations.

ACKNOWLEDGMENTS

One of the authors (B.-Q. M.) would like to acknowledge the Alexander von Humboldt Foundation for financial support.

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