Flavor and charge symmetry in the parton distributions of the nucleon

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Recent calculations of charge symmetry violation (CSV) in the valence quark distributions of the nucleon have revealed that the dominant symmetry breaking contribution comes from the mass associated with the spectator quark system. Assuming that the change in the spectator mass can be treated perturbatively, we derive a model-independent expression for the shift in the parton distributions of the nucleon. This result is used to derive a relation between the charge- and flavor-asymmetric contributions to the valence quark distributions in the proton, and to calculate the CSV contribution to the nucleon sea. The CSV contribution to the Gottfried sum rule is also estimated, and found to be small. [S0556-2813(98)02208-0]

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INTRODUCTION

Recent measurements of the flavor [1–3] and spin [4] dependence of quark distributions in the nucleon have led to a revival of interest in the soft QCD physics that determines the shape and normalization of parton distributions [5], and has led to a reexamination of some of the fundamental assumptions embodied in the parametrizations [6] used to describe data from high energy experiments. In particular, the violation of charge symmetry in the valence quark distributions has been calculated by a number of authors [7–10] in the context of quark models, and surprisingly large violations, as large as 5–10 %, have been found at large x_{Bj} [7]. Although charge symmetry is assumed in all phenomenological parton distributions, there is not a great deal of direct experimental evidence which justifies this assumption. The strongest upper limit on parton charge symmetry violation (CSV) can be obtained by comparing the F_2 structure function for charged lepton deep inelastic scattering with the F_2 structure function measured in neutrino-induced charged current reactions. The CCFR group has recently carried out such a test using the most recent available data [11]. They compared their neutrino cross sections on iron with the F_2 structure functions extracted from muon-deuterium measurements of the NMC group [1]. In the region $0.1 \leqslant x \leqslant 0.3$, these recent experiments can place upper limits of about 6% on parton CSV. For larger x the upper limits are substantially larger, while for $x<0.1$ the present data appear to indicate a substantial violation of charge symmetry. A number of experiments have been suggested which would measure directly charge symmetry violation in parton distributions [12].

In this paper, we combine the approaches of Refs. [7] and [8] and examine the violation of charge symmetry in the valence and sea quark distributions of the nucleon in a manner independent of the choice of any particular quark model. In the following section, we present the formalism used to produce parton distributions from quark model wave functions, and examine the variation of those distributions with small changes in the mass of the system of spectator quarks. In the next section, we use these results to examine the changes in the valence quark distribution due to SU(4) violation via color magnetism, and charge symmetry violation via quark masses and electromagnetism. Combining these results, we obtain a wave-function-independent prediction relating the dominant contribution to the CSV valence distribution to the well-known difference between the u and d valence distributions. In the penultimate section, we estimate the charge-symmetry violating sea quark distributions, assuming that the dominant CSV effect comes from the mass and electromagnetic differences of the participating quarks, rather than from the dependence of the quark wave functions on charge symmetry, as is the case for the valence quark CSV contributions [7]. Additionally, we make simple estimates of the contribution of CSV to the Gottfried sum rule. Finally, we compare our results with those of other authors and discuss their implications.

QUARK DISTRIBUTIONS FROM QUARK MODELS

For the purposes of this paper, we shall adopt the Adelaide method for calculating quark distributions from model wave functions [7]. The starting point for the method is the reduction of quark distributions to the form [13]

$$q(x)=M\int \frac{d^3k}{(2\pi)^3}|\Psi_+(k)|^2\delta(E_q-k_3-Mx), \qquad (1)$$

where x is the Bjorken scaling variable, M is the mass of the target, $\Psi_+(k)$ is the light cone wave function for the struck quark in momentum space, and E_q is the energy of the struck quark. An analogous expression gives the antiquark distributions

$$\overline{q}(x)=M\int \frac{d^3k}{(2\pi)^3}|\Psi_+^\dagger(k)|^2\delta(E_q-k_3-Mx). \qquad (2)$$

The essence of the Adelaide approach lies in the kinematic assumption that the three-quark system can be divided into the struck quark plus a diquark spectator system, and that the distribution of masses of the spectator system is sufficiently sharply peaked that the diquark can be thought of as an on-shell system with a definite mass. This completely

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specifies the kinematics of the problem and allows the quark energy appearing in the delta functions of Eqs. (1) and (2) to be replaced by the difference between the target mass and the on-shell diquark energy. Since the direct calculation of these distributions is not our interest here, we will not reduce this expression further, but simply note that the expression for the quark distribution can be reduced to a single integral over the momentum space wave function of the struck quark [7], and is guaranteed to have the correct support as a function of x_{Bj} regardless of the properties of the wave functions used to evaluate the integral.

SYMMETRY BREAKING

With the exception of Ref. [8], the approach to study the violation of parton distribution symmetries has been to calculate entire distributions in the framework of a given quark model and then to compare the results from small variations in the model parameters. In Refs. [7] and [14], the dependence of the valence quark distribution on the model wave function and diquark mass parameter has been studied in the context of examining charge and flavor symmetry in the valence sector. The dependence of the valence distributions on the details of the quark wave function was found to be small in comparison to the effects generated by changes in the diquark mass parameter. Similar conclusions were reached in Ref. [9], where charge-symmetry-breaking effects were studied using a different approach to connect quark model wave functions to valence distributions. Based on these results, we shall assume that the dominant contribution to the breaking of parton distribution symmetries is generated not by the changes in struck quark wave functions, but by the changes in the kinematic constraints brought about by shifts in the masses of the spectator quark systems and the nucleon itself. This allows a quark-model-independent prediction for the change in parton distributions when the symmetry is broken. To see this, begin with Eq. (1) for the valence quark distribution, and make a small variation in the mass of the spectator diquark, $M_d \to M_d^0 + \delta M_d$, where M_d^0 is the diquark mass in the symmetric limit, and δM_d is the shift in the diquark mass due to symmetry breaking. Expanding Eq. (1) to first order in δM, we obtain

$$\delta q(x) = -M \int d^3k |\Psi_+(k)|^2 \times \frac{\delta M_d M_d^0}{E_d^0} \delta'(M(1-x)+k_3-E_d^0(\mathbf{k})), \qquad (3)$$

where quantities with the superscript 0 are taken in the symmetric limit, and $E_d(\mathbf{k})$ is the diquark energy. Changing the derivative of the delta function to a derivative in x, using kinematics to solve for E_d^0, and neglecting the transverse momentum of the diquark, one finally obtains

$$\delta q(x) \approx \delta M_d \frac{d}{dx}\left[\frac{2M_d^0(1-x)}{M^2(1-x)^2+(M_d^0)^2} q^0(x) \right]. \qquad (4)$$

As we shall demonstrate in the following, this expression has two important advantages over explicit model realizations: First, as in Ref. [8], $\delta q(x)$ is determined in terms of $q^0(x)$, and so the change in the distribution can be extracted from measured distributions rather than models. Second, the size of the change is controlled by the diquark mass shift, which allows us to relate different symmetry-breaking effects to one another.

SYMMETRY BREAKING IN THE VALENCE SECTOR

In models where confinement is implemented via interactions which are independent of both spin and flavor, the wave functions of the up and down valence quarks are identical, leading via Eq. (1) to the prediction

$$\frac{d_v(x)}{u_v(x)} = \frac{1}{2}, \qquad (5)$$

where $u_v(x)$ and $d_v(x)$ are, respectively, the up and down valence quark distributions, and the factor of 2 merely expresses the relative normalization of the distributions. These relations, which relate distributions with different flavors within the same hadron, are somewhat inappropriately termed flavor symmetries [15]. Such symmetries are a consequence of dynamical assumptions about the nature of confinement in QCD. In this instance, the quark model SU(4) spin-isospin symmetry gets broken by the color hyperfine interaction, leading to the well-known dominance of u_v over d_v at large x.

This symmetry breaking has been modeled by Close and Thomas [14], who considered the spin-flavor correlations in the SU(4) nucleon wave function and the mass splitting of spin-1 and spin-0 diquark pairs brought about by the color hyperfine interaction. In this picture, the valence distribution depends not on the flavor of the struck quark, but rather on the spin of the spectator diquark system. Explicitly,

$$u_v(x) = \frac{3}{2} q_v^{S=0}(x) + \frac{1}{2} q_v^{S=1}(x), \quad d_v(x) = q_v^{S=1}(x), \quad (6)$$

where the superscript refers to the spin of the diquark spectator. In the SU(4)-symmetric limit, $q_v^{S=0}(x) = q_v^{S=1}(x)$ and Eq. (5) is recovered. Color hyperfine effects are included via a Hamiltonian of the form

$$H_{\mathrm{hf}} = v \sum_{i>j} \sum_{a=1,\ldots,8} \sigma_i \cdot \sigma_j \lambda_i^a \lambda_{aj}, \qquad (7)$$

with $\frac{1}{2}\sigma_i$ the spin of quark i, λ_i^a the corresponding color generator, and $v = 75$ MeV is normalized by the N-Δ splitting. The diquark masses are shifted according to

$$\delta_{\mathrm{hf}} M_d^{S=1} = -\frac{1}{3}, \quad \delta_{\mathrm{hf}} M_d^{S=0} = \frac{2}{3} v, \qquad (8)$$

so that, from Eq. (4),

$$\delta_{\mathrm{hf}} q_v^{S=1}(x) = -\frac{1}{3} \delta_{\mathrm{hf}} q_v^{S=0}(x) \qquad (9)$$

and

$$\delta_{\mathrm{hf}} q_v^{S=1}(x) = \frac{2d_v(x) - u_v(x)}{6}. \qquad (10)$$

Interestingly, this pattern of symmetry breaking predicts that the valence distributions measured in leptoproduction from neutron targets are precisely the SU(4)-symmetric distributions.

Now we turn our attention to the case of charge symmetry violation, which relates distributions of opposite isospin in targets of opposite isospin. In the charge symmetric limit,

$$u_v^p(x)=d_v^n(x), \quad d_v^p(x)=u_v^n(x), \tag{11}$$

where, for example, $u_v^p(x)$ denotes the distribution of u quarks in the proton, $d_v^n(x)$ is the distribution of d quarks in the neutron, and we have analogous definitions for the minority quark distributions.

At the quark level, charge symmetry is violated by quark mass and electromagnetic effects and is generally expected at the level of 1%. Since both of these effects are isovector, there is no CSV contribution to the mass of the isoscalar diquark, and we may write, for the minority quark distributions,

$$d_v^p(x)=q_v^{S=1}(x)+\frac{1}{2}\,\delta_{\rm CSV}q_v^{S=1}(x),$$

$$u_v^n(x)=q_v^{S=1}(x)-\frac{1}{2}\,\delta_{\rm CSV}q_v^{S=1}(x), \tag{12}$$

where $\delta_{\rm CSV}q_v^{S=1}(x)$ is the change in the quark distribution generated by the shift in the $I_3=\pm 1$ diquark masses via Eq. (4). Since the only difference between the CSV case and the flavor/SU(4)-symmetry-violating distribution is the value of δM_d, the two distributions are the same up to a normalization, so that

$$\delta_{\rm CSV}q_v^{S=1}(x)=\frac{\delta_{\rm CSV}M_d}{\delta_{\rm hf}M_d}\,\delta_{\rm hf}\,q_v^{S=1}(x)$$

$$=\frac{\delta_{\rm CSV}M_d}{\delta_{\rm hf}M_d}\left(\frac{2d_v(x)-u_v(x)}{6}\right). \tag{13}$$

From the bag model, a robust estimate of the isovector diquark mass splitting is -4 MeV [16], yielding $\delta_{\rm CSV}M_d/\delta_{\rm hf}M_d\approx 0.08$. Using the CTEQ4 LQ distributions [6] to parametrize the valence distributions, the charge-symmetry-violating contribution to the minority quark valence distribution due to the shift in the diquark mass is shown in Fig. 1. We plot the quantity $x\,\delta d_v(x)=x[d_v^p(x)-u_v^n(x)]$, where the CSV terms are calculated from Eq. (13). Also shown are result of bag model calculations using two different approaches to extract the quark distributions from model wave functions [10]. The reasonable agreement between the analytic result of Eq. (13) and the two different model calculations of CSV gives us confidence that the model calculations give rather robust predictions of valence quark charge symmetry violation.

To complete the calculation of the CSV distributions we must include the effect of the proton-neutron mass difference. This proceeds in essentially the same manner outlined in the last section, with the slight subtlety that the variation with respect to the target mass should be taken keeping the product Mx fixed, as the mass is implicit in the definition of

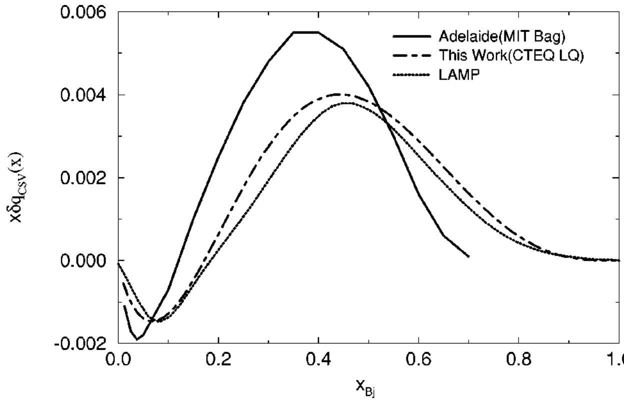

FIG. 1. Diquark mass contribution to charge-symmetry-violating quark distributions for minority valence quarks. Curves show $x[d_v^p(x)-u_v^n(x)]$ defined from Eqs. (12) and (13). Curves were calculated using the CTEQ4 LQ distribution at $Q^2=0.49$ GeV^2. Also shown are model calculations from Refs. [7] and [9].

x (see Ref. [9] for an explanation of this point). The resulting addition to the CSV distribution yields

$$\delta d_v(x)\equiv d_v^p(x)-u_v^n(x)=0.013[u_v(x)-2d_v(x)]$$
$$-\frac{\delta M}{M}\,\frac{d\;d_v(x)}{dx},$$

$$\delta u_v(x)\equiv u_v^p(x)-d_v^n(x)=-\frac{\delta M}{M}\,\frac{du_v(x)}{dx}, \tag{14}$$

where $\delta M=-1.3$ MeV is the proton-neutron mass difference. The resulting CSV distributions (multiplied by x) are shown in Fig. 2 for the CTEQ4 LQ distributions, along with the CSV contribution to the minority quark distribution $[x\,\delta d_v(x)]$ from Fig. 1 (the dash-dotted curve in Fig. 2).

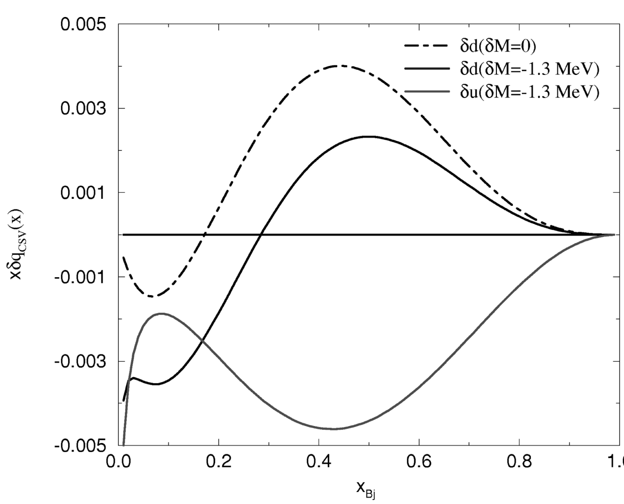

FIG. 2. Charge-symmetry-violating quark distributions for majority (δu) and minority (δd) valence quarks. Solid curves include effects of both $n-p$ mass difference and diquark mass contribution; dot-dashed curve shows minority quark CSV neglecting the $n-p$ mass difference. Curves were calculated using the CTEQ LQ distribution at $Q^2=0.49$ GeV^2.

As a consequence of the singularities in the CTEQ parametrizations, the nucleon mass correction diverges nonintegrably at $x=0$; cf. Eq. (4). This reflects the inadequacy of the diquark spectator approximation in this region, which is dominated by states having one or more pairs of sea quarks. At larger x, where the calculation is more reliable, the nucleon mass correction partially cancels out the change due to the diquark mass shift, a result which can be expected on the basis of Eq. (3). In accordance with the results of Refs. [7–9], the magnitudes of the CSV contribution to the minority and majority quark distributions are roughly comparable, so that the smaller minority quark distribution is more sensitive to CSV than the majority distribution.

CHARGE SYMMETRY VIOLATION IN THE NUCLEON SEA

There has been much interest in the question of flavor symmetry violation in the nucleon sea, following the precise measurement of the Gottfried sum rule [17] by the NMC group [1]. The Gottfried sum rule is obtained by integrating the F_2 structure functions for lepton-induced deep inelastic scattering (DIS) on protons and neutrons,

$$S_G=\int_0^1 \frac{dx}{x}[F_2^{\mu p}(x)-F_2^{\mu n}(x)]=\frac{1}{3}+\frac{8}{9}(P_{\bar{u}/p}-P_{\bar{u}/n})+\frac{2}{9}(P_{\bar{d}/p}-P_{\bar{d}/n}), \tag{15}$$

where we define the sea quark probabilities as

$$P_{\bar{u}/p}\equiv\int_0^1 \overline{u^p}(x)dx.$$

In deriving Eq. (15) we have used the normalization of the valence quark distributions; if we assume parton charge symmetry, we obtain the ''standard'' form for the Gottfried sum rule,

$$S_G=\frac{1}{3}-\frac{2}{3}(P_{\bar{d}/p}-P_{\bar{u}/p}).$$

By measurements over the range $0.004\leqslant x\leqslant 0.8$ for muon DIS on proton and deuteron targets, and extrapolation over the unmeasured region, the NMC group obtained $S_G=0.235\pm0.026$. If one assumes charge symmetry, this result implies an asymmetry in the probabilities for finding up and down sea quarks in the proton,

$$P_{\bar{d}/p}-P_{\bar{u}/p}=0.147\pm0.039.$$

However, as was pointed out by Ma [18], we could alternatively assume flavor symmetry but not charge symmetry for the sea quark distributions, in which case the NMC result would imply

$$P_{\bar{u}/p}-P_{\bar{u}/n}=-0.088\pm0.023.$$

Experimental upper limits on sea quark charge symmetry cannot at present rule out parton CSV contributions. So it is possible that the Gottfried sum rule result arises either from CSV effects or from a combination of flavor symmetry and charge symmetry violation.

In this section we will estimate the magnitude of charge symmetry violation for sea quarks and the contribution this might make to the Gottfried sum rule. The effect of flavor symmetry or charge symmetry violation on the sea quark distributions is complicated by the fact that there are no sum rules constraining the normalization of the sea quark distributions. Indeed, in the standard parametrizations [6] at high momentum scales the total number of sea quarks is infinite, a fact that has been used to suggest that fractionally small CSV in the sea may lead to sizable contributions to the Gottfried sum rule [18]. Since this contribution, regardless of its source, is independent of the momentum scale at which it is measured [19], it is amenable to modeling at a relatively low scale, say, $Q^2=0.5$ GeV^2, where it has been argued that the number of sea quarks in the nucleon is finite [20].

SUM RULE CONTRIBUTIONS

The CSV contributions to the sea separate, somewhat artificially, into two classes: strong CSV effects which change the number of sea quarks in the nucleon (and potentially contribute to the Gottfried sum rule) and weak CSV effects which change the shape of the sea distributions without altering their normalization. We shall begin by considering the first of these classes, since the extent to which the Gottfried sum rule violation is a reflection of CSV rather than flavor symmetry violation may provide an important constraint on the second class of CSV contributions. The simplest perturbative estimate of the size of the CSV contribution is obtained by modeling the nucleon as a valence state coupled to a small number of states with an additional quark-antiquark pair,

$$|N\rangle=Z\left(|N_{\rm val}\rangle+\sum_\alpha A_{\alpha/N}|N_{\rm val}q_\alpha\overline{q}_\alpha\rangle\right), \tag{16}$$

with Z a normalization, A_α the amplitude for finding the ''extra'' quark-antiquark pair of flavor $\alpha=u,d,s$, and $N_{\rm val}$ a three-quark state with the same third component of isospin as the original three-quark state. Assuming flavor symmetry, the amplitude for creating an extra quark pair of flavor α is given, in perturbation theory, by

$$A_{\alpha/N}\approx\frac{\lambda}{(M_{5Q\alpha}-M_{\rm nuc})}, \tag{17}$$

where M_{5Q} is the mass of the four-quark, antiquark state, and λ is a typical hadronic mass scale determined by the strong coupling constant and the details of the wave function. If charge symmetry is also good, this amplitude is independent of the flavor of the quark-antiquark pair, so that the probability for creating a quark-antiquark pair of flavor α is

$$P_{\alpha/N}\approx\frac{\lambda^2}{(M_{5Q\alpha}-M_{\rm nuc})^2}, \tag{18}$$

TABLE I. Charge-asymmetric contributions to the mass of multiquark composite systems. $m_u - m_d = -2.7$ MeV and $\epsilon_{\rm EM} = 4.2$ MeV are determined by fitting the neutron-proton and isovector diquark mass splittings.

Quark content	$\delta M_{\rm CSB}$
uu	$2(m_u - m_d) + \frac{1}{3}\epsilon_{\rm EM} = -4$ MeV
ud	0
uud	$(m_u - m_d) + \frac{1}{3}\epsilon_{\rm EM} = -1.3$ MeV
$uuud$	$2(m_u - m_d) + \epsilon_{\rm EM} = -1.2$ MeV
$uudd$	0
$uuds$	$(m_u - m_d) = -2.7$ MeV
$uud\bar{s}$	$(m_u - m_d) + \frac{2}{3}\epsilon_{\rm EM} = 0.1$ MeV
$uuud\bar{u}$	$3(m_u - m_d) = -8.1$ MeV
$uudd\bar{d}$	$-(m_u - m_d) + \frac{2}{3}\epsilon_{\rm EM} = 5.5$ MeV
$uuds\bar{s}$	$(m_u - m_d) + \frac{1}{3}\epsilon_{\rm EM} = -1.3$ MeV

which, apart from Pauli effects which violate the flavor symmetry we have assumed, is essentially the result of Donoghue and Golowich [21].

To incorporate charge symmetry violation into this picture requires only an estimate of the mass shift due to quark mass and electromagnetic effects. We parametrize this difference via a term that counts the number of up and down quark masses in the composite system, and through the inclusion of an electromagnetic contribution to the energy which we assume is proportional to the sum of the pairwise products of the charges of the constituents. The quark mass difference and electromagnetic energy are then fit to the mass shifts of the diquark and nucleon, and the results are extrapolated to systems with more quarks. This procedure clearly neglects a great deal of the physics of these systems, but should be sufficient to provide an estimate of the energy scales involved. The resulting mass shifts between charge conjugate systems can then be written

$$\delta M_{\rm CSB} = (N_u - N_d)(m_u - m_d) - \delta\Sigma\,\epsilon_{\rm EM}, \tag{19}$$

where N_f is the number of quarks plus antiquarks of flavor f in the system in question, $\delta\Sigma$ is the change in the sum of the products of charges under charge conjugation, and $\epsilon_{\rm EM}$ is the average electromagnetic energy of each quark pair. The mass shifts that result from this procedure are shown in Table I.

Expanding to first order in the symmetry-violating terms yields relations between the number of sea quarks of charge conjugate flavors in the proton and neutron:

$$P_{\bar{u}/p} = P_{\bar{d}/n}\left(1 - \frac{2(m_u - m_d) - \frac{1}{3}\epsilon_{\rm EM}}{m_q}\right)$$

$$P_{\bar{d}/p} = P_{\bar{u}/n}\left(1 + \frac{2(m_u - m_d) - \frac{1}{3}\epsilon_{\rm EM}}{m_q}\right)$$

$$P_{\bar{s}/p} = P_{\bar{s}/n}, \tag{20}$$

where $m_q = 360$ MeV is the constituent quark mass in the symmetric limit. Remarkably, since the energy required to make a pair of a particular flavor is the same for both the proton and neutron in this parametrization, there is no contribution to the Gottfried sum rule in the flavor-symmetric limit. In a more sophisticated treatment of quark mass and electromagnetic effects we expect that the CSV contribution will be nonzero, but since a contribution to the Gottfried sum rule needs to be odd under the combined operation of flavor and charge symmetry, which requires additional charge-symmetry and flavor-violating effects, the CSV contribution to the Gottfried sum rule will be suppressed below the natural scales for CSV effects arising from quark mass differences and electromagnetic terms [proportional to $(m_u - m_d)/m_q$ and α, respectively].

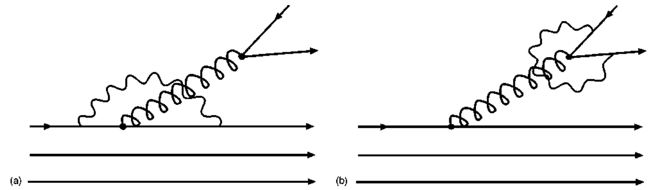

FIG. 3. Photons dressing the quark-gluon vertex during the production of sea quarks. The probability of producing a sea quark pair will depend on the charge of the created quarks (b) and on the quark that initially produced the gluon (a).

Another source for CSV in the sea is the possibility of a charge dependence of the quark gluon coupling constant. By dressing the quark-gluon vertex with a photon as in Figs. 3(a) and 3(b), the effective quark-gluon coupling for u quarks is different than that for d quarks [22], so that the probability of creating a $q\bar{q}$ pair becomes dependent on both the flavor of the pair created and the flavor of the quark that emitted the gluon.

At low momentum scales, the effective gluon coupling to a quark of flavor f is given by

$$\alpha_{sf}^{\rm eff} = \alpha_s(Q^2)[1 + e_f^2 V(b)], \tag{21}$$

where α_s is the strong coupling constant, $b = \Lambda^2/Q^2$, e_f is the quark charge, and

$$V(b) = \frac{\alpha}{4\pi}\left(-1 - \frac{\pi^2}{3} - \ln b - \ln^2 b\right), \tag{22}$$

with α the electromagnetic coupling. Rewriting this, we get

$$\alpha_s^u = \alpha_{s0} + \delta\alpha_s, \quad \alpha_s^d = \alpha_{s0} - \delta\alpha_s, \tag{23}$$

where now

$$\delta\alpha_s = \frac{\alpha_s(Q^2)}{6} V(b) \tag{24}$$

is the charge-asymmetric piece of the strong coupling and $\alpha_{s0} = \frac{1}{2}(\alpha_s^u + \alpha_s^d)$.

Assuming that the sea quarks at low momentum scales are generated by the valence quarks, we have

$$P_{\bar{u}_p} \propto (2\alpha_s^u + \alpha_s^d)\alpha_s^u, \quad P_{\bar{u}_n} \propto (\alpha_s^u + 2\alpha_s^d)\alpha_s^u,$$

$$P_{\bar{d}_p} \propto (2\alpha_s^u + \alpha_s^d)\alpha_s^d, \quad P_{\bar{d}_n} \propto (\alpha_s^u + 2\alpha_s^d)\alpha_s^d, \tag{25}$$

from which we obtain, to first order in the CSV terms,

$$P_{\bar{u}/n} = P_{\bar{d}/p}, \quad P_{\bar{d}/n} = P_{\bar{u}/p}\left(1 - 4\frac{\delta\alpha_s}{\alpha_{s0}}\right). \tag{26}$$

Since the valence quarks provide a source of flavor asymmetry, there is a contribution to the Gottfried sum rule. Using the CTEQ distributions to calculate $P_{\bar{u}/p}=0.365$ and $\Lambda=200$ MeV, we find the CSV contribution to the Gottfried sum rule to be 6.3×10^{-4}, which is far too small to explain the observed deviation. Similarly, there is a small excess of strange quarks in the proton over those in the neutron, according to

$$P_{\bar{s}/p}-P_{\bar{s}/n}=+2\frac{\delta\alpha_s}{\alpha_{s0}}P_{\bar{s}/p}\approx 2\times10^{-4}. \tag{27}$$

Having eliminated the possibility of a large CSV contribution to the Gottfried sum rule, we return briefly to the possibility that the largest part of the sum rule comes from violation of flavor symmetry, and that the violation of flavor symmetry leads to a CSV contribution to the sum as well. Combining Eq. (20) with a flavor-asymmetric sea yields

$$\delta_{\mathrm{CSV}}S_G=\frac{5}{9}\left(\frac{2(m_u-m_d)-\frac{1}{3}\epsilon_{\mathrm{EM}}}{m_q}\right)(P_{\bar{d}/p}-P_{\bar{u}/p})\approx-0.0012, \tag{28}$$

using the CTEQ parton distributions. Our estimated CSV contribution is still far too small to affect significantly the extraction of the flavor asymmetry. We conclude that the prospects for a large contribution to the Gottfried sum rule from sea quark CSV are extremely slim, at least within the assumptions in our calculation of charge-symmetry-violating effects.

WEAK CHARGE SYMMETRY VIOLATION IN THE SEA

Since we have been unable to produce a mechanism for generating a CSV distribution whose integral is significantly different from zero, we are led to investigate the possibility of weak charge symmetry breaking, where the shapes of the sea distributions in the neutron and proton are different, but their normalizations remain the same. By analogy with the CSV effects in the valence distributions, we shall proceed by postulating that the four spectator partons can be assumed to belong to a tetraquark, and that the mass of the recoiling tetraquark can be assumed to be approximately constant with a value roughly equal to the sum of the constituent quark masses. Since there is a greater variety of states available to the four-spectator-parton system, this assumption is much less certain than the analogous assumption in the valence case, but it will allow for an exploration of the magnitudes involved in the problem.

The basic argument proceeds as in the case of the valence distributions, by calculating the shift in the tetraquark mass produced by the symmetry-violating interactions and expanding to get

$$\begin{aligned}\delta\bar{q}(x)&=\bar{q}^p(x)-\bar{q}^n(x)\\&=\delta M_T\frac{d}{dx}\left[\frac{2M_T^0(1-x)}{M^2(1-x)^2+(M_T^0)^2}\,\bar{q}^0(x)\right],\end{aligned} \tag{29}$$

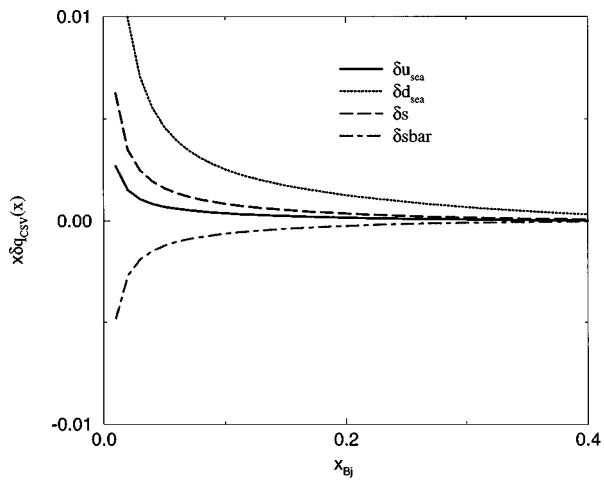

FIG. 4. Charge-symmetry-violating sea quark distributions. The solid, dotted, dashed, and dot-dashed curves are $x\delta\bar{u}=x(\bar{u}^p-\bar{d}^n)$, $x\delta\bar{d}=x(\bar{d}^p-\bar{u}^n)$, $x\delta s=x(s^p-s^n)$, and $x\delta\bar{s}=x(\bar{s}^p-\bar{s}^n)$, respectively.

where M_T^0 is the charge-symmetric tetraquark mass, and $\bar{q}_0(x)$ is the antiquark distribution in the symmetric limit. For the light quark sea, we have used a tetraquark mass of 1440 MeV, roughly 4 times the constituent quark mass. If, as many models assert, pionic effects dominate the sea at these low scales, this assumption will underestimate the size of the CSV contribution to the light quark sea. For the systems containing strange quarks, we have assumed a constituent quark mass of 500 MeV. In addition to this correction, there will be a correction due the change in the nucleon mass introduced by CSV, which is calculated in the same fashion as the analogous contribution for the valence quarks. The values of the CSV-induced mass shifts for strange and non-strange tetraquarks are listed in Table I, and the resulting CSV sea distributions are shown in Fig. 4.

Just as in the case of the valence distributions, the large contribution to sea quark asymmetries at very small x is a consequence of the singular form of the parton distributions in this region, and indicates the breakdown of the tetraquark picture have used here. At larger x, the relative size of $\delta\bar{d}$ over $\delta\bar{u}$ reflects the fact that the tetraquark spectator has $I_3=0$ when a $\bar{d}$ is struck, so that there is no tetraquark mass shift to partially cancel the nucleon mass shift, as is the case when $\bar{u}$ is struck. For the strange CSV distributions, a similar cancellation occurs for the spectator tetraquark when an s quark is struck, but since this cancellation depends sensitively on the parameters chosen in Table I, we conclude that this result may be highly model dependent and therefore untrustworthy. In general, we do not find surprisingly large contributions for any of the sea quark distributions.

SUMMARY

In this paper, we have used the Adelaide approach to calculating quark model parton distributions to calculate the effect of CSV on the parton distributions of the proton. For the valence quarks, we verify in a model-independent fashion the anomalously large CSV effects observed in the minority valence quark distribution by several authors [7–9], and we relate these distributions to the difference between the u and d valence distributions. Since there are little data to constrain the size of the CSV distributions, proposed tests of CSV [12] will provide a sensitive test of the physics contained in QCD-inspired models of the nucleon.

Additionally, we have made estimates of the size of CSV effects in the nucleon sea. First, we assume a strong violation of charge symmetry, which would alter the value of sum rules which assume charge symmetry. For the Gottfried sum rule, there are no CSV contributions unless there is a simultaneous violation of flavor symmetry in either the sea or valence quarks. In either case, we estimate that the CSV contributions to the Gottfried sum rule are much smaller than are suggested by experiment. We have also estimated the weak CSV contribution to the nucleon sea, using methods similar to the valence quark CSV calculations. Again, we find that the charge-symmetry-violating distributions are extremely small, and highly unlikely to make significant contributions to any observable.

Note added in proof. A result similar to ours may be obtained by first integrating over the delta function in Eq. (1), and then neglecting the transverse momentum in the z component of the quark current. The expression for the CSV distribution is identical to Eq. (4), except that the x derivative now only acts on $q(x)$. The corresponding change in the CSV contribution to the minority valence quark distribution is a 25% reduction from our result. We thank A. W. Thomas for bringing this possibility to our attention.

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