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Isospin symmetry breaking in the chiral quark model

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We discuss the isospin symmetry breaking (ISB) of the valence- and sea-quark distributions between the proton and the neutron in the framework of the chiral quark model. We assume that isospin symmetry breaking is the result of mass differences between isospin multiplets and then analyze the effects of isospin symmetry breaking on the Gottfried sum rule and the NuTeV anomaly. We show that, although both flavor asymmetry in the nucleon sea and the ISB between the proton and the neutron can lead to the violation of the Gottfried sum rule, the main contribution is from the flavor asymmetry in the framework of the chiral quark model. We also find that the correction to the NuTeV anomaly is in an opposite direction, so the NuTeV anomaly cannot be removed by isospin symmetry breaking in the chiral quark model. It is remarkable that our results of ISB for both valence- and sea-quark distributions are consistent with the Martin-Roberts-Stirling-Thorne parametrization of quark distributions.

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I. INTRODUCTION

Isospin symmetry was originally introduced to describe almost identical properties of strong interaction of the proton and the neutron by turning off their electromagnetic interaction, i.e., their charge information. This symmetry is commonly expected to be a precise symmetry [1,2], and its breaking is assumed to be negligible in the phenomenological or experimental analysis. This is, in general, true, since electromagnetic interactions are weak compared with strong interactions. However, it is possible for isospin symmetry breaking (ISB) to have an important influence on some experiments, especially on the parton distributions. Therefore, it is necessary to analyze it carefully.

The isospin symmetry between the proton and the neutron originates from the SU(2) symmetry between u and d quarks, which are isospin doublets with isospin $I = 1/2$ and isospin three-components (I_3) $1/2$ and $-1/2$, respectively. The isospin symmetry at parton level indicates that the $u(d, \bar{u}, \bar{d})$-quark distribution in the proton is equal to the $d(u, \bar{d}, \bar{u})$-quark distribution in the neutron. Accordingly, the ISBs of both valance-quark and sea-quark distributions are defined, respectively, as

$$\begin{aligned} \delta u_{\mathrm{V}}(x) &= u_{\mathrm{V}}^{\mathrm{p}}(x) - d_{\mathrm{V}}^{\mathrm{n}}(x), \qquad \delta d_{\mathrm{V}}(x) = d_{\mathrm{V}}^{\mathrm{p}}(x) - u_{\mathrm{V}}^{\mathrm{n}}(x), \\ \delta \bar{u}(x) &= \bar{u}^{\mathrm{p}}(x) - \bar{d}^{\mathrm{n}}(x), \qquad \delta \bar{d}(x) = \bar{d}^{\mathrm{p}}(x) - \bar{u}^{\mathrm{n}}(x), \end{aligned} \tag{1}$$

where $q_{\mathrm{V}}^{\mathrm{N}}(x) = q^{\mathrm{N}}(x) - \bar{q}^{\mathrm{N}}(x)$ ($q = u, d$, N = p, n).

ISB at the parton level and its possible consequences for several processes were first investigated by one of us [3]. It was pointed out that both flavor asymmetry in the nucleon sea and isospin symmetry breaking between the proton and the neutron can lead to the violation of the Gottfried sum rule reported by the New Muon Collaboration [4,5]. The possibility of distinguishing these two effects was also discussed in detail [6].

In 2002, the NuTeV Collaboration [7] extracted $\sin^2\theta_{\mathrm{W}}$ by measuring the ratios of neutral current to charged current ν and $\bar{\nu}$ cross sections on iron targets. The reported $\sin^2\theta_{\mathrm{W}} = 0.2277 \pm 0.0013(\mathrm{stat}) \pm 0.0009(\mathrm{syst})$ has approximately 3 standard deviations above the world average value $\sin^2\theta_{\mathrm{W}} = 0.2227 \pm 0.0004$ measured in other electroweak processes. This remarkable deviation is called the NuTeV anomaly and was discussed in a number of papers from various aspects, including new physics beyond the standard model [8], the nuclear effect [9], nonisoscalar targets [10], and strange-antistrange asymmetry [11–13]. Moreover, the possible influence of ISB on this measurement was also studied in a series of papers [14–20]. However, the correction from ISB to the NuTeV anomaly is still not conclusive.

The Martin-Roberts-Stirling-Thorne (MRST) group [21] provided some evidence to support the ISB effects on parton distributions of both valance and sea quarks and included ISB in the parametrization based on experimental data. They obtained the ISB of valance quarks as

$$\delta u_{\mathrm{V}} = -\delta d_{\mathrm{V}} = \kappa(1-x)^4 x^{-0.5}(x - 0.0909), \tag{2}$$

where $-0.8 \leq \kappa \leq +0.65$ with a 90% confidence level, and the best fit value is $\kappa = -0.2$. They also obtained the ISB of sea quarks, as can be deduced from Eqs. (28) and (29) in Ref. [21],

$$\delta \bar{u}(x) = k\bar{u}^{\mathrm{p}}(x), \qquad \delta \bar{d}(x) = k\bar{d}^{\mathrm{p}}(x), \tag{3}$$

with the best fit value $k = 0.08$.

In this paper, we calculate the ISB of the valance- and sea-quark distributions between the proton and the neutron in the chiral quark model and discuss some possible effects of ISB. We assume that the ISB between the proton and the neutron is entirely from the mass difference between

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isospin multiplets at both hadron and parton levels.[1] In Sec. II, we compute ISB in the chiral quark model, with the constituent-quark-model results as the bare constituent-quark-distribution inputs. Then, we calculate the ISB effect on the violation of the Gottfried sum rule. In Sec. III, we discuss the ISB correction to the measurement of a weak angle and point out the significant influence on the NuTeV anomaly. In Sec. IV, we provide summaries of the paper.

II. ISOSPIN SYMMETRY BREAKING IN THE CHIRAL QUARK MODEL

The chiral quark model, established by Weinberg [22] and developed by Manohar and Georgi [23], has an apt description of its important degrees of freedom in terms of quarks, gluons, and Goldstone (GS) bosons at momentum scales relating to hadron structure. This model is successful in explaining numerous problems, including the violation of the Gottfried sum rule from the aspect of flavor asymmetry in the nucleon sea [24,25], the proton spin crisis [26–28], and the NuTeV anomaly resulting from the strange-antistrange asymmetry [13], and has been widely recognized as an effective theory of QCD at the low-energy scale.

In the chiral quark model, the minor effects of the internal gluons are negligible. The valence quarks contained in the nucleon fluctuate into quarks plus GS bosons, which spontaneously break chiral symmetry. Then, the effective interaction Lagrangian is

$$L = \bar{\psi}(iD_\mu + V_\mu)\gamma^\mu\psi + ig_A\bar{\psi}A_\mu\gamma^\mu\gamma_5\psi + \cdots, \quad (4)$$

where

$$\psi = \begin{pmatrix} u \\ d \\ s \end{pmatrix} \quad (5)$$

is the quark field and $D_\mu = \partial_\mu + igG_\mu$ is the gauge-covariant derivative of QCD. G_μ stands for the gluon field, g stands for the strong coupling constant, and g_A stands for the axial-vector coupling constant. V_μ and A_μ are the vector and the axial-vector currents, which are defined as

$$\begin{pmatrix} V_\mu \\ A_\mu \end{pmatrix} = \frac{1}{2}(\xi^+\partial_\mu\xi \pm \xi\partial_\mu\xi^+), \quad (6)$$

where $\xi = \exp(i\Pi/f)$, and Π has the form

$$\Pi \equiv \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & \frac{-2\eta}{\sqrt{6}} \end{pmatrix}. \quad (7)$$

[1]As the mass difference between isospin multiplets, especially that between u and d quarks, is not entirely due to charge difference, we refer to such an effect as isospin symmetry breaking instead of charge symmetry breaking, as it is called in some papers.

Expanding V_μ and A_μ in powers of Π/f, one gets $V_\mu = 0 + O(\Pi/f)^2$ and $A_\mu = i\partial_\mu\Pi/f + O(\Pi/f)^2$. The pseudoscalar decay constant is $f \simeq 93$ MeV. Thus, the effective interaction Lagrangian between GS bosons and quarks in the leading order becomes [24]

$$L_{\Pi q} = -\frac{g_A}{f}\bar{\psi}\partial_\mu\Pi\gamma^\mu\gamma_5\psi. \quad (8)$$

Based on the time-ordered perturbative theory in the infinite momentum frame, all particles are on-mass-shell, and the factorization of the subprocess is automatic, so we can express the quark distributions inside a nucleon as a convolution of a constituent-quark distribution in a nucleon and the structure functions of a constituent quark. Since the η is relatively heavy, we neglect the minor contribution from its suppressed fluctuation in this paper. Then, the light-front Fock decompositions of constituent-quark wave functions are

$$|U\rangle = \sqrt{Z_u}|u_0\rangle + a_{\pi^+}|d\pi^+\rangle + \frac{a_{u\pi^0}}{\sqrt{2}}|u\pi^0\rangle + a_{K^+}|sK^+\rangle, \quad (9)$$

$$|D\rangle = \sqrt{Z_d}|d_0\rangle + a_{\pi^-}|u\pi^-\rangle + \frac{a_{d\pi^0}}{\sqrt{2}}|d\pi^0\rangle + a_{K^0}|sK^0\rangle, \quad (10)$$

where Z_u and Z_d are the renormalization constants for the bare constituent u quark $|u_0\rangle$ and d quark $|d_0\rangle$, respectively, and $|a_\alpha|^2$ $(\alpha = \pi, K)$ are the probabilities to find GS bosons in the dressed constituent-quark states $|U\rangle$ and $|D\rangle$. In the chiral quark model, the fluctuation of a bare constituent quark into a GS boson and a recoil bare constituent quark is given as [29]

$$q_j(x) = \int_x^1 \frac{dy}{y} P_{j\alpha/i}(y) q_i\left(\frac{x}{y}\right), \quad (11)$$

where $P_{j\alpha/i}(y)$ is the splitting function, which gives the probability of finding a constituent quark j carrying the light-cone momentum fraction y together with a spectator GS boson α,

$$P_{j\alpha/i}(y) = \frac{1}{8\pi^2}\left(\frac{g_A\bar{m}}{f}\right)^2 \int dk_T^2 \frac{(m_j - m_i y)^2 + k_T^2}{y^2(1-y)[m_i^2 - M_{j\alpha}^2]^2}. \quad (12)$$

m_i, m_j, and m_α are the masses of the i- and j-constituent quarks and the pseudoscalar meson α, respectively, and $\bar{m} = (m_i + m_j)/2$ is the average mass of the constituent quarks. $M_{j\alpha}^2 = (m_j^2 + k_T^2)/y + (m_\alpha^2 + k_T^2)/(1-y)$ is the square of the invariant mass of the final state. We can also write the internal structure of GS bosons in the following form:

$$q_k(x) = \int \frac{dy_1}{y_1}\frac{dy_2}{y_2} V_{k/\alpha}\left(\frac{x}{y_1}\right) P_{\alpha j/i}\left(\frac{y_1}{y_2}\right) q_i(y_2), \quad (13)$$

where $V_{k/\alpha}(x)$ is the quark k distribution function in α and satisfies the normalization $\int_0^1 V_{k/\alpha}(x)dx = 1$.

When we take ISB into consideration, the renormalization constant Z should take the form

$$\begin{aligned} Z_u &= 1 - \langle P_{\pi^+}\rangle - \tfrac{1}{2}\langle P_{u\pi^0}\rangle - \langle P_{K^+}\rangle, \\ Z_d &= 1 - \langle P_{\pi^-}\rangle - \tfrac{1}{2}\langle P_{d\pi^0}\rangle - \langle P_{K^0}\rangle, \end{aligned} \tag{14}$$

where $\langle P_\alpha\rangle \equiv \langle P_{j\alpha/i}\rangle = \langle P_{\alpha j/i}\rangle = \int_0^1 x^{n-1} P_{j\alpha/i}(x)\mathrm{d}x$ [29]. It is conventional to specify the momentum cutoff function at the quark–GS-boson vertex as

$$g_A \rightarrow g'_A \exp\left[\frac{m_i^2 - M_{j\alpha}^2}{4\Lambda^2}\right], \tag{15}$$

where $g'_A = 1$, following the large N_c argument [30], and Λ is the cutoff parameter, which is determined by the experimental data of the Gottfried sum and the constituent-quark-mass inputs for the pion. Such a form factor
has the correct t- and u-channel symmetry, $P_{j\alpha/i}(y) = P_{\alpha j/i}(1-y)$. Then, one can obtain the quark-distribution functions in the proton [29],

$$\begin{aligned} u(x) &= Z_u u_0(x) + P_{u\pi^-/d} \otimes d_0(x) + V_{u/\pi^+} \otimes P_{\pi^+ d/u} \\ &\quad \otimes u_0(x) + \tfrac{1}{2} P_{u\pi^0/u} \otimes u_0(x) + V_{u/K^+} \otimes P_{K^+ s/u} \\ &\quad \otimes u_0(x) + \tfrac{1}{2} V_{u/\pi^0} \otimes [P_{\pi^0 u/u} \otimes u_0(x) + P_{\pi^0 d/d} \\ &\quad \otimes d_0(x)], \\ d(x) &= Z_d d_0(x) + P_{d\pi^+/u} \otimes u_0(x) + V_{d/\pi^-} \otimes P_{\pi^- u/d} \\ &\quad \otimes d_0(x) + \tfrac{1}{2} P_{d\pi^0/d} \otimes d_0(x) + V_{d/K^0} \otimes P_{K^0 s/d} \\ &\quad \otimes d_0(x) + \tfrac{1}{2} V_{d/\pi^0} \otimes [P_{\pi^0 u/u} \otimes u_0(x) + P_{\pi^0 d/d} \\ &\quad \otimes d_0(x)], \\ \bar{u}(x) &= V_{\bar{u}/\pi^-} \otimes P_{\pi^- u/d} \otimes d_0(x) + \tfrac{1}{2} V_{\bar{u}/\pi^0} \\ &\quad \otimes [P_{\pi^0 u/u} \otimes u_0(x) + P_{\pi^0 d/d} \otimes d_0(x)], \\ \bar{d}(x) &= V_{\bar{d}/\pi^+} \otimes P_{\pi^+ d/u} \otimes u_0(x) + \tfrac{1}{2} V_{\bar{d}/\pi^0} \\ &\quad \otimes [P_{\pi^0 u/u} \otimes u_0(x) + P_{\pi^0 d/d} \otimes d_0(x)], \end{aligned} \tag{16}$$

where the constituent-quark distributions u_0 and d_0 are normalized to two and one, respectively. Convolution integrals are defined as

$$\begin{aligned} P_{j\alpha/i} \otimes q_i &= \int_x^1 \frac{\mathrm{d}y}{y} P_{j\alpha/i}(y) q_i\left(\frac{x}{y}\right), \\ V_{k/\alpha} \otimes P_{\alpha j/i} \otimes q_i &= \int_x^1 \frac{\mathrm{d}y_1}{y_1} \int_{y_1}^1 \frac{\mathrm{d}y_2}{y_2} V_{k/\alpha}\left(\frac{x}{y_1}\right) P_{\alpha j/i}\left(\frac{y_1}{y_2}\right) q_i(y_2). \end{aligned} \tag{17}$$

In addition, $V_{k/\alpha}(x)$ follows the relationship

$$\begin{aligned} V_{u/\pi^+} &= V_{\bar{d}/\pi^+} = V_{d/\pi^-} = V_{\bar{u}/\pi^-} = 2V_{u/\pi^0} = 2V_{\bar{u}/\pi^0} \\ &= 2V_{d/\pi^0} = 2V_{\bar{d}/\pi^0} = \tfrac{1}{2} V_\pi, \\ V_{u/K^+} &= V_{d/K^0}. \end{aligned} \tag{18}$$

We postulate that the bare-quark distributions are isospin-symmetric between the proton and the neutron, so we can obtain the quark distributions of the neutron by interchanging u_0 and d_0. Employing the quark distributions of the chiral quark model, we get the Gottfried sum determined by the difference between the proton and the neutron structure functions,

$$\begin{aligned} S_G &= \int_0^1 \frac{\mathrm{d}x}{x}[F_2^p(x) - F_2^n(x)] \\ &= \frac{1}{9}\int_0^1 \mathrm{d}x[4u^p(x) + 4\bar{u}^p(x) - 4u^n(x) - 4\bar{u}^n(x) \\ &\quad + d^p(x) + \bar{d}^p(x) - d^n(x) - \bar{d}^n(x)] \\ &= \frac{1}{3} + \int_0^1 \mathrm{d}x\left\{\frac{8}{9}[\bar{u}^p(x) - \bar{u}^n(x)] + \frac{2}{9}[\bar{d}^p(x) - \bar{d}^n(x)]\right\} \\ &= \frac{1}{3} - \frac{8}{9}\langle P_{\pi^-}\rangle + \frac{2}{9}\langle P_{\pi^+}\rangle + \frac{5}{18}(\langle P_{u\pi^0}\rangle - \langle P_{d\pi^0}\rangle). \end{aligned} \tag{19}$$

We assume that the ISB is entirely from the mass difference between isospin multiplets. In this paper, we adopt $(m_u + m_d)/2 = 330$ MeV, $m_{\pi^\pm} = 139.6$ MeV, $m_{\pi^0} = 135$ MeV, $m_{K^\pm} = 493.7$ MeV, and $m_{K^0} = 497.6$ MeV. We choose two sets of the mass difference between u and d quarks, namely $\delta m = 4$ MeV and $\delta m = 8$ MeV, respectively, in order to show the dependence on this important parameter. Based on Eq. (19) and the experimental data of the Gottfried sum [5], one can find that the appropriate value for Λ_π is 1500 MeV. However, one cannot determine Λ_K in the same method, because $\langle P_K\rangle$ in the Gottfried sum is canceled out. Usually, it is assumed that $\Lambda_K = \Lambda_\pi = 1500$ MeV [29,31]. However, it is implied by the $SU(3)_f$ symmetry breaking that $\langle P_K\rangle$ should be smaller, and, accordingly, one should adopt a smaller Λ_K. In this paper, we adopt a wide range of Λ_K from 900 to 1500 MeV. In addition, the parton distributions of mesons are the parametrization GRS98 given by Gluck-Reya-Stratmann [32], since the parametrization is more approximate to the actual value,

$$\begin{aligned} V_\pi(x) &= 0.942x^{-0.501}(1 + 0.632\sqrt{x})(1-x)^{0.367}, \\ V_{u/K^+}(x) &= V_{d/K^0}(x) = 0.541(1-x)^{0.17} V_\pi(x). \end{aligned} \tag{20}$$

We should point out that, in principle, it is possible that the parton distributions of different mesons in the same multiplet are different, and this can contribute to ISB simultaneously. However, in this paper, we simply neglect this possibility, and calculations in future can be improved if we have a better understanding of the quark structure of mesons. Moreover, we have to specify constituent-quark distributions u_0 and d_0, but there is no proper parametrization of them because they are not directly related to

observable quantities in experiments. In this paper, we adopt the constituent-quark-model distributions [33] as inputs for constituent-quark distributions. For the proton, we have

$$u_0(x) = \frac{2x^{c_1}(1-x)^{c_1+c_2+1}}{\mathrm{B}[c_1+1, c_1+c_2+2]},$$
$$d_0(x) = \frac{x^{c_2}(1-x)^{2c_1+1}}{\mathrm{B}[c_2+1, 2c_1+2]}, \tag{21}$$

where $\mathrm{B}[i, j]$ is the Euler beta function. Such distributions satisfy the number and the momentum sum rules

$$\int_0^1 u_0(x)\mathrm{d}x = 2, \qquad \int_0^1 d_0(x)\mathrm{d}x = 1,$$
$$\int_0^1 x u_0(x)\mathrm{d}x + \int_0^1 x d_0(x)\mathrm{d}x = 1. \tag{22}$$

$c_1 = 0.65$ and $c_2 = 0.35$ are adopted in the calculation, following the original choice [33,34].

We display the ISB of the valance- and sea-quark distributions in Figs. 1–3, respectively. It is shown that in most regions, $x\delta u_{\mathrm{V}}(x) > 0$ and $x\delta\bar{u}(x) > 0$, and on the contrary that $x\delta d_{\mathrm{V}}(x) < 0$ and $x\delta\bar{d}(x) < 0$. Our predictions that $x\delta\bar{u}(x) > 0$ and $x\delta\bar{d}(x) < 0$ are consistent with the MRST parametrization [21], and, moreover, the shapes of $x\delta\bar{u}(x)$ and $x\delta\bar{d}(x)$ are similar to the best phenomenological fitting results given by the MRST group. We should point out that our results are analogous to the results calculated in the framework of the meson cloudy model by Cao and Signal [18], and the shapes and magnitudes of $x\delta\bar{u}(x)$ and $x\delta\bar{d}(x)$ are similar to the results given in the framework of the radiatively generated ISB [19], but with different signs. It can also be found that the difference between various choices of Λ_K is minor, but the different choices of δm can have remarkable influence on the distributions. Especially, larger δm can lead to larger ISB, and this is concordant with our principle that ISB results from the mass difference between isospin multiplets at both hadron and parton levels. From the figures, we can see that $\delta u_{\mathrm{V}}(x)$ reaches a maximum value at $x \approx 0.5$, and $\delta d_{\mathrm{V}}(x)$ has a minimum value at $x \approx 0.4$. It should also be noted that $\delta q_{\mathrm{V}}(x)$ $(q = u, d)$ must have at least one zero point due to the valance-quark–normalization conditions. We should also point out that at large x, $\delta u_{\mathrm{V}}/u_{\mathrm{V}} \approx -\delta d_{\mathrm{V}}/d_{\mathrm{V}}$, and this implies that the magnitudes of the ISB for u_{V} and d_{V} are almost the same, but with opposite signs. Moreover, although both flavor asymmetry in the nucleon sea and the ISB between the proton and the neutron can lead to the violation of the Gottfried sum rule, the main contribution is from the flavor asymmetry in the framework of the chiral quark model.

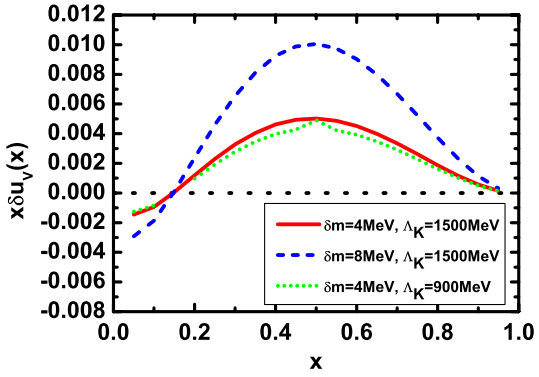

FIG. 1 (color online). The ISB of the u_{V}-quark distribution $x\delta u_{\mathrm{V}}(x)$ versus x in the chiral quark model with different inputs. The red solid line is the result with $\delta m = 4$ MeV and $\Lambda_K = 1500$ MeV as inputs. The blue dashed line is the result with $\delta m = 8$ MeV and $\Lambda_K = 1500$ MeV as inputs. The green dotted line is the result with $\delta m = 4$ MeV and $\Lambda_K = 900$ MeV as inputs.

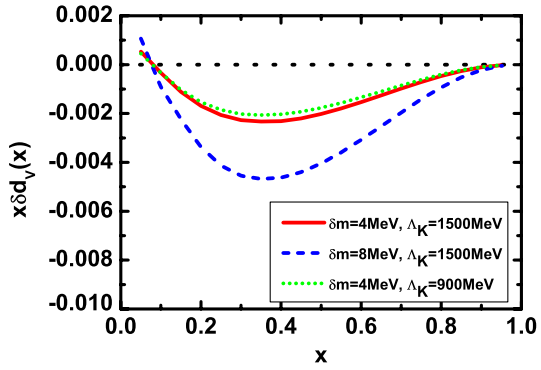

FIG. 2 (color online). The ISB of the d_{V}-quark distribution $x\delta d_{\mathrm{V}}(x)$ versus x in the chiral quark model with different inputs. The red solid line is the result with $\delta m = 4$ MeV and $\Lambda_K = 1500$ MeV as inputs. The blue dashed line is the result with $\delta m = 8$ MeV and $\Lambda_K = 1500$ MeV as inputs. The green dotted line is the result with $\delta m = 4$ MeV and $\Lambda_K = 900$ MeV as inputs.

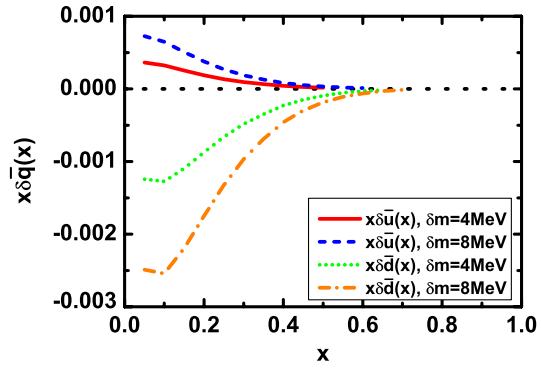

FIG. 3 (color online). The ISB of the sea-quark distributions $x\delta\bar{q}(x)$ versus x in the chiral quark model. The red solid line and the blue dashed line are the behaviors of $x\delta\bar{u}(x)$, with $\delta m = 4$ MeV and $\delta m = 8$ MeV, respectively. The green dotted line and the orange dash-dotted line are the behaviors of $x\delta\bar{d}(x)$, with $\delta m = 4$ MeV and $\delta m = 8$ MeV, respectively.

III. THE CONTRIBUTION FROM ISOSPIN SYMMETRY BREAKING TO THE NUTEV ANOMALY

The measured $\sin^2\theta_W$ by the NuTeV Collaboration is closely related to the Paschos-Wolfenstein (PW) ratio [35]

$$R^- = \frac{\langle\sigma^{\nu N}_{NC}\rangle - \langle\sigma^{\bar{\nu}N}_{NC}\rangle}{\langle\sigma^{\nu N}_{CC}\rangle - \langle\sigma^{\bar{\nu}N}_{CC}\rangle} = \frac{1}{2} - \sin^2\theta_W, \tag{23}$$

where $\langle\sigma^{\nu N}_{NC}\rangle$ is the neutral-current–inclusive cross section for a neutrino on an isoscalar target. If we take the ISB between the proton and the neutron into account, we obtain

$$R^-_N = \frac{\langle\sigma^{\nu N}_{NC}\rangle - \langle\sigma^{\bar{\nu}N}_{NC}\rangle}{\langle\sigma^{\nu N}_{CC}\rangle - \langle\sigma^{\bar{\nu}N}_{CC}\rangle} = R^- + \delta R^{ISB}_{PW}, \tag{24}$$

where δR^{ISB}_{PW} is the correction from the ISB to the PW ratio and takes the form

$$\delta R^{ISB}_{PW} = \left(\frac{1}{2} - \frac{7}{6}\sin^2\theta_W\right)\frac{\int_0^1 x[\delta u_V(x) - \delta d_V(x)]dx}{\int_0^1 x[u_V(x) + d_V(x)]dx}, \tag{25}$$

with $u_V(x)$ and $d_V(x)$ standing for valance-quark distributions of the proton. We show the renormalization constant Z, the total momentum fraction of valance quarks $Q_V = \int_0^1 x[u_V(x) + d_V(x)]dx$, and the correction of the ISB to the NuTeV anomaly ΔR^{ISB}_{PW}, with different δm and Λ_K as inputs in Table I. It can be found that the ISB correction is of the order of magnitude of 10^{-3} and is more significant with a larger δm or Λ_K. Our result is consistent with the range $-0.009 \le \Delta R^{ISB}_{PW} \le +0.007$, which is derived based on the parametrization given by the MRST group [21]. We should stress that the correction is remarkable, since the NuTeV anomaly can be totally removed if $\Delta R_{PW} = -0.005$, and, consequently, we should pay special attention to ISB in such problem. It is also worthwhile to point out that the correction is in an opposite direction to remove the NuTeV anomaly in the chiral quark model. Such a conclusion is the same as that given in the baryon-meson fluctuation model [20], but the value is one or 2 orders of magnitude larger. Our result of the ISB correction to the NuTeV anomaly differs from the results in Refs. [17,19].

TABLE I. The renormalization constant, the total momentum fraction of valance quarks, and the correction of the ISB to the NuTeV anomaly in the chiral quark model.

δm (MeV)	Λ_K (MeV)	Z_u	Z_d	Q_V	ΔR^{ISB}_{PW}
4	900	0.7497	0.7463	0.8451	0.0008
4	1200	0.7220	0.7185	0.8222	0.0008
4	1500	0.6932	0.6896	0.7985	0.0009
8	900	0.7515	0.7444	0.8455	0.0016
8	1200	0.7239	0.7165	0.8227	0.0017
8	1500	0.6953	0.6874	0.7990	0.0019

IV. SUMMARY

In this paper, we discuss the ISB of the valance-quark and sea-quark distributions between the proton and the neutron in the framework of the chiral quark model. We assume that isospin symmetry breaking is the result of mass differences between isospin multiplets. Then, we analyze the effects of isospin symmetry breaking on the Gottfried sum rule and the NuTeV anomaly. We show that, although both flavor asymmetry in the nucleon sea and the ISB between the proton and the neutron can lead to the violation of the Gottfried sum rule, the main contribution is from the flavor asymmetry in the framework of the chiral quark model. It is remarkable that our results of ISB for both the valence-quark and sea-quark distributions are consistent with the MRST parametrization of the ISB of valance- and sea-quark distributions. Moreover, we find that the correction to the NuTeV anomaly is in an opposite direction, so the NuTeV anomaly cannot be removed by isospin symmetry breaking in the chiral quark model. However, its influence is remarkable and should be taken into careful consideration. Therefore, it is important to do more precision experiments and careful theoretical studies on isospin symmetry breaking.

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