The $s$-$\bar{s}$ asymmetry in nucleon and "NuTeV anomaly"

F. X. Wei $^{1,2)}$, B. S. Zou$^{1,2,3)}$

1) Institute of High Energy Physics, CAS, P.O.Box 918 (4), Beijing 100049
2) Graduate University, Chinese Academy of Sciences, Beijing 100049
3) Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000

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Abstract

The $s$-$\bar{s}$ asymmetry in nucleon sea is an important observable for understanding nucleon structure and strong interaction. There have been many theoretical attempts on this subject and recently on its relation to the "NuTeV anomaly". Calculations with different theoretical frameworks lead to different conclusions. Here assuming a newly proposed penta-quark configuration for the $s$-$\bar{s}$ asymmetry in nucleon, we examine its contribution to the "NuTeV anomaly", with a result of about $10 \sim 20\%$.

1 Introduction

As a modern theory of strong interaction, quantum chromodynamics (QCD) is supposed to give us the possibility to describe all properties of observed hadrons, such as the structure of nucleon. However, due to its nonperturbative difficulty in infrared region and the complexity of hadronic phenomena, this is still impossible. We have to rely on the QCD-inspired phenomenological models, such as bag model and constituent quark model, to describe effectively some properties of observed hadrons. With their close relation to the experimental observables, the deeper investigations to these models are expected to give some hints for the solutions of QCD, or strong interaction. The strangeness in nucleon may provide important observables for studying various models.

*weifx@ihep.ac.cn
†zoubs@ihep.ac.cn
According to the quark parton model, which is the consequence of QCD, a nucleon is composed of 3 valence quarks plus a fluctuating number of gluons and sea quark anti-quark pairs. Since the strange quarks are the lightest quarks different from nucleon’s valence quarks, the strangeness in the nucleon is of particular interest for understanding the role of sea quarks. Experiments have indicated that strange quarks do, in fact, play a fundamental role in understanding properties of the nucleon [1]. It could be interpreted that the existence of strangeness in nucleon is a nonperturbative effect. Then the question can be asked, in what kind of form do these strange quarks exist in the nucleon? Many models have been proposed. The widely used ones are meson cloudy model and chiral constituent quark model.

Recently, in order to explain the empirical indications for a positive strangeness magnetic moment of the proton, a new possible configuration has been proposed for the strangeness in the proton [2], i.e., the $\bar{s}$ in the ground state and the $uuds$ system in the $P$ state. The new configuration can also reproduce other strangeness properties of the proton [3, 4] and has been successfully extended to explain properties of other baryons [5, 6]. In order to further check the validity of the new configuration, study of the asymmetry of parton distribution functions $s(x)$ and $\bar{s}(x)$ versus the momentum fraction $x$ and its consequence would be a proper choice. The possible asymmetry of $s(x)$ and $\bar{s}(x)$ has been discussed in Ref. [7] by Signal and Thomas and further explored by other authors [8]. The analysis of related experimental data [9, 10] seems not conclusive, and the limit of the $s-\bar{s}$ asymmetry quoted in [10] is $-0.001 < [S^-] < 0.004$, where $[S^-] = \int_0^1 dx [s(x) - \bar{s}(x)]$. The refreshed interest on this subject is prompted by the “NuTeV anomaly” [11] - a 3σ deviation of the NuTeV measured value of $\sin^2\theta_W$ ($0.2277 \pm 0.0013 \pm 0.0009$) [12] from the world average of other measurements ($0.2227 \pm 0.0004$). The contribution of $s-\bar{s}$ asymmetry to this departure has been discussed in Refs. [11, 13], and calculated in Ref. [14, 15, 16] in the framework of meson-baryon model and chiral constituent quark model, respectively. It is rather puzzling that the two pictures give entirely different results.

In this article, we will discuss the difference of the meson-baryon model and chiral constituent quark model related to the strange content in nucleon; then calculate the second moment of the strange-antistrange distributions $[S^-]$ and its contribution to the “NuTeV anomaly” with a newly proposed penta-quark model for the strangeness in the proton [2].

2 The strange parton distribution in nucleon

The strange quark in nucleon sea, as well as $u$ and $d$, can be broken down into perturbative and nonperturbative parts. The perturbative part of $s\bar{s}$ due to short-range fluctuation of gluon field has no contribution to the $s-\bar{s}$ asymmetry. We only focus on the nonperturbative part, which
can exist over the longer time than the interaction time in the deep inelastic process and hence contributes to the $s$-$\bar{s}$ asymmetry observables. As discussed in precious section, there are many models about the nonperturbative strange sea quarks. These models can be classified into two sorts: meson-baryon configuration and quark-meson configuration. The dynamical information of the two pictures can be obtained from relevant scattering experiments.

In the meson-baryon configuration, the nucleon sometimes fluctuates to a baryon plus a meson. Contributions to the strange sea can come from fluctuations involving a hyperon, such as $p(uud) \rightarrow \Lambda(uds) + K^+(u\bar{s})$. In this example, the contribution to the strange quark distribution $s(x)$ comes from the strange quark in the $\Lambda$, while the contribution to the anti-strange distribution $\bar{s}(x)$ comes from the anti-strange quark in the kaon. Then the strange distribution can be calculated by using the valence parton distribution of $\Lambda$ and kaon, respectively. Because of the different fluctuation functions and different parton distributions in $\Lambda$ and $K^+$, the calculated results for $s(x)$ and $\bar{s}(x)$ are different. However, there are some theoretical uncertainties in this picture. First, the dynamical quantities, such as coupling constants, which are derived from reproducing experimental data on scattering processes, may be invalid in applying directly to the interior of the nucleon. The off-shell extension suffers large uncertainty. Secondly, the parton distributions of $\Lambda$ and $K^+$, which can not be directly calculated from first principle, would also bring large uncertainties to the results. We will see that these two problems could be avoided in the penta-quark model.

In the chiral constituent quark model with quark-meson configuration, the meson octet was introduced as the Goldstone particles, which are the consequences of the spontaneously broken chiral symmetry (SBCS). Therefore, the quarks are dressed by mesons. The relevant degrees of freedom in this configuration are constituent quarks and Goldstone bosons (The effect of gluon can be negligible at low energy). In this picture, the constituent quarks couple directly to the GS bosons, for example, $u \rightarrow K^+(u\bar{s}) + s$. The contribution to $\bar{s}(x)$ comes from the parton distribution in $K^+$, and contribution to $s(x)$ comes directly from dynamical process. Obviously, this picture also results in different $s(x)$ and $\bar{s}(x)$ distributions. Because the SBCS is included in this configuration, which is the nonperturbative effect of QCD, this picture is expected to provide a satisfactory representation for low energy hadron properties.

The results of the $s(x)$ and $\bar{s}(x)$ in these two configurations are very different, and even contradictory in some special regions [14, 16]. And the predicted $s$-$\bar{s}$ asymmetry from these two pictures differs by about two orders of magnitude. While the calculation within the framework of effective chiral quark model claims that the $s$-$\bar{s}$ asymmetry can account for about 60 – 100% of the NuTeV anomaly [16], the calculations with the meson-baryon configuration give much smaller results ranging from 1% [14] to 20% [15]. Besides the choice of parameters, the interaction of $s$ and $\bar{s}$ with other constituents may be the key to understand this difference.
In meson-baryon configuration, the $s$ is bound in the hyperon, while the $s$ is asymptotic free in the meson-quark picture. We reckon that the fluctuations of $q(u, d) \rightarrow Ks$ give a harder momentum distribution for $s$ than that given by nucleon fluctuations into $|BM\rangle$.

Recently a new possible configuration for the five quark components in the nucleon has been proposed [2, 3, 4, 5]. In the penta-quark model, the largest five quark components in the proton are $uudd\bar{d}$ and $uuds\bar{s}$ with the anti-quark in the orbital ground state and the four quarks in the mixed orbital $[31]_X$ symmetry, i.e., one in P-wave and three in S-wave. Therefore, the quark wave function for the proton may then be expanded as:

$$|p> = A_3q|uud> + A_{dd}|[ud][ud]\bar{d}> + A_{ss}|[ud][us]\bar{s}>$$

with the normalization condition $|A_3q|^2 + |A_{dd}|^2 + |A_{ss}|^2 = 1$. The fluctuation probability of the $dd\bar{d}$ and $ss\bar{s}$, which are interpreted as the probability to find the $uudd\bar{d}$ component and $uuds\bar{s}$ in a proton, can be obtained as $P_{dd} \equiv |A_{dd}|^2 = 12\%$ and $P_{ss} \equiv |A_{ss}|^2 = (12 - 48)\%$ by reproducing the observed light flavor sea quark asymmetry in the proton, $\bar{d} - \bar{u} = 0.12$ and the strangeness spin of the proton, $\Delta_s = -0.10 \pm 0.06$, respectively.

Since the $\bar{s}$ in $uuds\bar{s}$ system is in its ground state and the $uuds$ subsystem has mixed orbital symmetry $[31]_X$ which gives the possibility of 1/4 for $s$ to be in P-wave, this also gives naturally an $s-\bar{s}$ asymmetry.

3. NuTeV anomaly and contribution from $s-\bar{s}$ asymmetry

The "NuTeV anomaly" is an important open question in recent years. Although many sources of it have been explored in the past years [11, 13] there has been no consistent explanation on this subject. The measurement of Weinberg angle $\theta_W$ in Ref. [12] by NuTeV collaboration is closely related to the Paschos-Wolfestein(PW) relation [19], which is written as

$$R^- \equiv \frac{\sigma_{\nu N}^{pN} - \sigma_{\bar{\nu} N}^{pN}}{\sigma_{\nu N}^{pN} - \sigma_{\bar{\nu} N}^{pN}} \simeq 1/2 - \sin^2\theta_W + \delta R^-_A + \delta R^-_{QCD} + \delta R^-_{EW},$$

(2)

where the three $\delta$ terms are due to the nonisoscalarity of the target ($\delta R^-_A$), next-to-leading-order(NLO) and nonperturbative QCD effects ($\delta R^-_{QCD}$), and higher-order electroweak effects ($\delta R^-_{EW}$), respectively. The QCD corrections consist of three terms, which can be written as $\delta R^-_{QCD} = \delta R^-_s + \delta R^-_I + \delta R^-_{NLO}$, where the three $\delta$ terms in the right side are due to possible strange asymmetry ($\delta R^-_s$) and isospin violation ($u_{p,n} \neq d_{n,p}$) effects ($\delta R^-_I$) in the parton structure of nucleon, and NLO($O(\alpha_s)$) corrections($\delta R^-_{NLO}$), respectively. In this paper, we only
focus on the correction from $s-\bar{s}$ asymmetry, which contributes to $R^-$ as

$$\delta R_s^- \simeq -\left(\frac{1}{2} - \frac{7}{6} \sin^2 \theta_W\right) \frac{[S^-]}{[Q^-]},$$

where $[S^-] \equiv \int x[s(x) - \bar{s}(x)]dx$ quantifying the strangeness asymmetry, and $[Q^-] = \int x[q(x) - \bar{q}(x)]dx$ with $q(x) = [u(x) + d(x)]/2$ representing the isoscalar valence quark distribution. In order to solve the NuTeV anomaly, the sign of $[S^-]$ needs to be positive, i.e. $[S^-] > 0$.

Generally, for a nucleon in its $|A, B\rangle$ configuration created in the fluctuation process $|N\rangle \to |A\rangle + |B\rangle$ with $s$ and $\bar{s}$ in $|A\rangle$ and $|B\rangle$, respectively, the $s$ distribution can be expressed as a convolution of fluctuation function $f_{AB/N}(x)$ with the valence parton distribution $s_A(x)$ in the state $|A\rangle$; and the distribution of $\bar{s}$ can be expressed as a convolution of fluctuation function $f_{BA/N}(x)$ with the valence parton distribution $\bar{s}_B(x)$ in the state $|B\rangle$ [18]. Explicitly, the strange and anti-strange quark distributions in the nucleon can be written as

$$s(x) = \int_x^1 \frac{dy}{y} f_{AB/N}(y)s_A\left(\frac{x}{y}\right),$$

$$\bar{s}(x) = \int_x^1 \frac{dy}{y} f_{BA/N}(y)\bar{s}_B\left(\frac{x}{y}\right),$$

with general constraints $f_{AB/N}(x) = f_{BA/N}(1-x)$ and $\int_0^1 dx f_{BA/N}(x) = P_{AB/N}$, where $P_{AB/N}$ is the probability to find the $|A, B\rangle$ configuration in a nucleon.

The fluctuation function $f_{AB/N}(x)$ is interpreted as probability to find $|A\rangle$ with a fraction $x$ of the nucleon momentum, while the $f_{BA/N}(x)$ is the probability to find $|B\rangle$ with a fraction $x$ of nucleon momentum. It reflects the dynamical information of the fluctuation process, which is the nonperturbative effect closely related to QCD at large distances. The dynamical mechanism behind this process may be important for further research.

However, in our case with penta-quark configuration, the thing is getting simpler. The fluctuation function is just $f_{5q/N}(x) = P_{5q/N}\delta(x-1)$. The dynamical information of the fluctuation process is included into the probability which can be obtained from experimental data. This could be one of advantages of the penta-quark model.

The next step in our calculation is to determine parton distribution in the penta-quark configuration. Simple harmonic oscillator wave functions are used with radial part as

$$\varphi^S(k) = \frac{1}{(\alpha^2 \pi)^{3/4}} \exp\left(-\frac{k^2}{2\alpha^2}\right),$$

$$\varphi^P(k) = \frac{k}{\alpha} \varphi^S(k),$$

for the S-state and P-state, respectively. Here $\alpha^2 = m_s \omega$ with $\omega$ the harmonic oscillator parameter. With these wave functions, the distributions of $s$ and $\bar{s}$ in $uuds\bar{s}\bar{s}$ system can be
obtained by the method in Ref. [20, 21], in which the distributions of $s(\bar{s})$ in the five-quark constituent can be expressed as

\begin{align}
    s_{5q}(x) &= \int d\vec{k} \delta(Mx - k^+) \left( \frac{3}{4} |\varphi^S(k)|^2 + \frac{1}{4} |\varphi^P(k)|^2 \right), \tag{8} \\
    \bar{s}_{5q}(x) &= \int d\vec{k} \delta(Mx - k^+) |\varphi^S(k)|^2, \tag{9}
\end{align}

where $M$ is the mass of the nucleon and $k^+$ the light-cone momentum of $s(\bar{s})$. The $s_{5q}(x)$ and $\bar{s}_{5q}(x)$ need to be normalized to 1.

Figure 1: The distributions of strange quarks (solid), $s(x)$, and antistrange quarks (dotted), $\bar{s}(x)$, in $uuds\bar{s}$ system.

Assuming commonly used values $m_s = m_{\bar{s}} = 400\text{MeV}$ and $\alpha = 300, 400, 600\text{MeV}$, the calculated results of $s_{5q}(x)$ and $\bar{s}_{5q}(x)$ are shown in Fig.1. Compared with $\bar{s}$, the $s(x)$ is softer in small $x$ and harder in large $x$ region. This variation can be easily understood in our theoretical frame, because in the penta-quark model the difference of $s(x)$ and $\bar{s}(x)$ in nucleon entirely results from the different distributions of $s$ and $\bar{s}$ in the $uuds\bar{s}$ component. While the $\bar{s}$ stays 100% in S-state, the $s$ has 25% probability staying in P-state. Hence the $s$ is more likely to take larger fraction of nucleon momentum. The distribution of $x\delta_s(x)$, with $\delta_s(x) = s(x) - \bar{s}(x)$ is shown in Fig. 2. The behavior of $x\delta_s(x)$ can be well understood in the penta-quark configuration where the $\bar{s}$ stays in the S-wave around the center of the system while $s$ in the $uuds$ has 25% probability in the P-state and gives harder distributions ($s(x)$) at large $x$ region.
Figure 2: The distribution of $x\delta_s(x)$, with $\delta_s(x) = s(x) - \bar{s}(x)$.

The results are sensitive to the value of parameter $\alpha$. Larger $\alpha$ leads to larger difference of $s(x)$ and $\bar{s}(x)$. This is because larger $\alpha$ gives larger difference between P-state and S-state. The choice of $m_s$ value makes little effect on the result.

From these strange parton distributions, assuming $\alpha = 400 MeV$ and $P_{s\bar{s}} = 20\%$, we obtain $[S^-] = 0.001$, which can account for 10% of the NuTeV anomaly. There is some evidence [5] suggesting that the $qqqs\bar{s}$ constituent is very compact with $\alpha$ around 1GeV. In this case, the $s-\bar{s}$ asymmetry would result in $[S^-] = 0.002$ and account for about 20% of NuTeV anomaly. The result from the newly proposed penta-quark configuration is much smaller than that from chiral constituent quark model [16], but comparable with that of meson-baryon models [14, 15]. As shown in Ref. [11, 13], there are many other uncertainties in theoretical framework for NuTeV experiment, and some other corrections may account for the NuTeV anomaly. The $s-\bar{s}$ asymmetry may not be the whole story.

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