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Understanding the proton spin "puzzle" with a new "minimal" quark model

B.-Q. Ma[1,a], I. Schmidt[2,b], and J.-J. Yang[2,3,c]

[1] Department of Physics, Peking University, Beijing 100871 and Institute of Theoretical Physics, Academia Sinica, Beijing 100080, PRC
[2] Departamento de Física, Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile
[3] Department of Physics, Nanjing Normal University, Nanjing 210097, PRC

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Abstract. We investigate the spin structure of the nucleon in an extended Jaffe-Lipkin quark model. In addition to the conventional $3q$ structure, different $(3q)(Q\bar{Q})$ admixtures in the nucleon wave function are also taken into account. The contributions to the nucleon spin from various components of the nucleon wave function are discussed. The effect due to the Melosh-Wigner rotation is also studied. It is shown that the Jaffe-Lipkin term is only important when antiquarks are negatively polarized. We arrive at a new "minimal" quark model, which is close to the naive quark model, in order to understand the proton spin "puzzle".

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1 Introduction

It has been more than a decade since the discovery of the Gourdin-Ellis-Jaffe sum rule (GEJ) [1] violation in the polarized deep inelastic scattering (DIS) experiment by the European Muon Collaboration [2]. The physics community was puzzled since the experimental data meant a surprisingly small contribution to the proton spin from the spins of the quarks, in contrast to the Gell-Mann-Zweig quark model in which the spin of the proton is totally provided by the spins of the three valence quarks. This gave rise to the proton spin "crisis" or spin "puzzle", and triggered a vast number of theoretical and experimental investigations on the spin structure of the nucleon. Among them, there was an interesting contribution to understand the spin of the nucleon within a "minimal" simple quark model [3], where it was observed that the nucleon has only a small amplitude to be a bare three-quark state $|qqq\rangle$, while the largest term in the wave function is $|qqqQ\bar{Q}\rangle$, in which $Q\bar{Q}$ denotes sea quark-antiquark pairs.

There was a prevailing impression that the proton spin structure is in conflict with the quark model. However, there has been an attempt to understand the proton spin puzzle within the quark model by using the Melosh-Wigner rotation effect [4,5], which comes from the relativistic effect of the quark intrinsic transversal motion inside the proton. It was pointed out [4–6] that the quark helicity (Δq) observed in polarized DIS is actually the quark spin defined in the light-cone formalism, and it is different from the quark spin (Δq_{QM}) as defined in the quark model. Thus the small quark helicity sum observed in polarized DIS is not necessarily in contradiction with the quark model in which the proton spin is provided by the valence quarks [5,7]. Recent progress [8–10] has also been made on the Melosh-Wigner rotation effect in other physical quantities related to the spin structure of the nucleon, and the significance of the Melosh-Wigner rotation connecting the spin states in the light-front dynamics and the conventional instant-form dynamics has been widely accepted. Thus it is necessary to check what can be obtained for the spin structure of the nucleon within the quark model, after we take into account the Melosh-Wigner rotation. Certainly our present understanding of the nucleon spin structure has been enriched from what we knew before the discovery of the GEJ sum rule violation, and we now know that both the sea quarks and the gluons play an important role in the spin structure of the nucleon. The purpose of this paper is to extend the simple Jaffe-Lipkin quark model to a more general framework, by including other necessary ingredients in the nucleon sea

[a] e-mail: mabq@phy.pku.edu.cn
[b] e-mail: ischmidt@fis.utfsm.cl
[c] e-mail: jjyang@fis.utfsm.cl

such as pseudoscalar mesons, whose addition is supported by available theoretical and experimental studies.

The paper is organized as follows. In sect. 2, we briefly review the Melosh-Wigner rotation effect in the quark model, and show that the introduction of an up(u)-down(d) quark flavor asymmetry of the Melosh-Wigner rotation factors can reproduce the present experimental data of the integrated spin structure functions for both the proton and the neutron [11–13], within a simple $SU(6)$ quark model with only three valence quarks. In sect. 3, we introduce the contribution from the higher Fock states $|BM\rangle = |qqqQ\bar{Q}\rangle$ in which the quark and antiquark of a quark-antiquark pair are rearranged non-perturbatively with the three valence quarks into a pseudoscalar meson and a baryon, and we write the configuration as a baryon-meson (BM) fluctuation [14]. It is shown that the consideration of the lowest $p(uudD\bar{D}) = n(udD)\pi^+(u\bar{D})$ fluctuation, which is supported by the observed Gottfried sum rule violation [15,16], introduces an u-d flavor asymmetric term in the quark contributions to the nucleon and produces a reasonable u-d Melosh-Wigner rotation asymmetry which is required to reproduce the data. In this section, we point out that the Jaffe-Lipkin term of quark-antiquark pairs (which are actually vector mesons in a baryon-meson fluctuation picture) will only be necessary when there is need for negatively polarized antiquarks. Thus, we present a new "minimal" quark model extension of Jaffe-Lipkin model, with three valence quarks, sea quark-antiquark pairs in terms of baryon-meson fluctuations where the mesons are either pseudoscalar or vector mesons, in order to understand the proton spin "puzzle" within the quark model framework. Finally, we present discussions and conclusions in sect. 4.

2 The naive quark model and the Melosh-Winger rotation

The spin-dependent structure functions for the proton and the neutron, when expressed in terms of the quark helicity distributions $\Delta q(x)$, should read

$$g_1^p(x) = \frac{1}{2}\left\{\frac{4}{9}\left[\Delta u(x) + \Delta\bar{u}(x)\right] + \frac{1}{9}\left[\Delta d(x) + \Delta\bar{d}(x)\right] + \frac{1}{9}\left[\Delta s(x) + \Delta\bar{s}(x)\right]\right\}, \quad (1)$$

$$g_1^n(x) = \frac{1}{2}\left\{\frac{1}{9}\left[\Delta u(x) + \Delta\bar{u}(x)\right] + \frac{4}{9}\left[\Delta d(x) + \Delta\bar{d}(x)\right] + \frac{1}{9}\left[\Delta s(x) + \Delta\bar{s}(x)\right]\right\}, \quad (2)$$

where the quantity $\Delta q(x)$ is defined by the axial current matrix element

$$\Delta q = \langle p, \uparrow| \,\bar{q}\gamma^+\gamma_5 q\, |p, \uparrow\rangle\,. \quad (3)$$

By expressing the quark axial charge or the quark helicity defined by $\Delta Q = \int_0^1 \mathrm{d}x[\Delta q(x) + \Delta\bar{q}(x)]$, we obtain

$$\Gamma^p = \int_0^1 \mathrm{d}x g_1^p(x) = \frac{1}{2}\left(\frac{4}{9}\Delta U + \frac{1}{9}\Delta D + \frac{1}{9}\Delta S\right), \quad (4)$$

$$\Gamma^n = \int_0^1 \mathrm{d}x g_1^n(x) = \frac{1}{2}\left(\frac{1}{9}\Delta U + \frac{4}{9}\Delta D + \frac{1}{9}\Delta S\right). \quad (5)$$

Two linear combinations of the axial charges, $\Delta Q^3 = \Delta U - \Delta D$ and $\Delta Q^8 = \Delta U + \Delta D - 2\Delta S$, are therefore given by

$$\Delta Q^3 = 6(\Gamma^p - \Gamma^n) = \Delta U - \Delta D = G_A/G_V = 1.261\,, \quad (6)$$

from neutron decay plus isospin symmetry, and by

$$\Delta Q^8 = \Delta U + \Delta D - 2\Delta S = 0.675\,, \quad (7)$$

from strangeness-changing hyperon decays plus flavor $SU(3)$ symmetry. Prior to the EMC experiment, the flavor singlet axial charge was evaluated by Gourdin and Ellis-Jaffe [1], assuming $\Delta S = 0$, to be

$$\Delta Q^0 = \Sigma = \Delta U + \Delta D + \Delta S = \Delta Q^8, \quad (8)$$

which is only true in the naive quark model without a gluonic contribution. Then one obtains, neglecting small QCD corrections, the GEJ sum rule

$$\Gamma^p = \frac{1}{12}\Delta Q^3 + \frac{1}{36}\Delta Q^8 + \frac{1}{9}\Delta Q^0 = 0.198\,, \quad (9)$$

which is larger than the observed experimental result of 0.126 from the EMC experiment [2], but now revised to be 0.136 [11–13].

The discovery of the GEJ sum rule violation came as a big surprise to the physics community since the sum of the quark helicities Σ inferred from eqs. (6) and (7) and the observed Γ^p, by allowing $\Delta S \neq 0$, gave the value

$$\Sigma = \Delta U + \Delta D + \Delta S = 0.020 \quad (10)$$

from the EMC data $\Gamma^p = 0.126$ [2], and

$$\Sigma = \Delta U + \Delta D + \Delta S \approx 0.30 \quad (11)$$

from the revised results $\Gamma^p = 0.136$ and $\Gamma^n = -0.03$, assuming $SU(3)$ symmetry [11–13]. This is in conflict with the naive expectation that the spin of the proton is totally provided by the spins of the three valence quarks in the naive $SU(6)$ quark model, if one interpreted the quark helicity ΔQ as the quark spin contribution to the proton spin. Many theoretical and experimental investigations have been devoted to understand this proton spin "puzzle" or spin "crisis" [17].

However, it has been pointed in refs. [4,5] that this puzzle can be easily explained within the naive $SU(6)$ quark model if one properly considers the fact that the observed quark helicity ΔQ is the quark spin defined in the light-cone formalism (infinite momentum frame), and it is different from the quark spin as defined in the rest frame of the nucleon (or in the quark model). In the light-cone or quark-parton descriptions, $\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$, where $q^{\uparrow}(x)$ and $q^{\downarrow}(x)$ are the probabilities of finding a quark or antiquark with longitudinal momentum fraction x and polarization parallel or anti-parallel to the proton helicity in the infinite momentum frame. However, in the nucleon rest frame one finds [4,6]

$$\Delta q(x) = \int [\mathrm{d}^2\mathbf{k}_\perp] M_q(x,\mathbf{k}_\perp) \Delta q_{QM}(x,\mathbf{k}_\perp)\,, \qquad (12)$$

with

$$M_q(x,\mathbf{k}_\perp) = \frac{(k^+ + m)^2 - \mathbf{k}_\perp^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2}\,, \qquad (13)$$

where $M_q(x,\mathbf{k}_\perp)$ is the contribution from the relativistic effect due to the quark transverse motion (or the Melosh-Wigner rotation effect), $q_{s_z=\frac{1}{2}}(x,\mathbf{k}_\perp)$ and $q_{s_z=-\frac{1}{2}}(x,\mathbf{k}_\perp)$ are the probabilities of finding a quark and antiquark with rest mass m and transverse momentum $\mathbf{k}_\perp$ and with spin parallel and anti-parallel to the rest proton spin, $\Delta q_{QM}(x,\mathbf{k}_\perp) = q_{s_z=\frac{1}{2}}(x,\mathbf{k}_\perp) - q_{s_z=-\frac{1}{2}}(x,\mathbf{k}_\perp)$, and $k^+ = x\mathcal{M}$, where $\mathcal{M}^2 = \sum_i \frac{m_i^2 + \mathbf{k}_{i\perp}^2}{x_i}$. The Melosh-Wigner rotation factor $M_q(x,\mathbf{k}_\perp)$ ranges from 0 to 1; thus Δq measured in polarized deep inelastic scattering cannot be identified with Δq_{QM}, the spin carried by each quark flavor in the proton rest frame or the quark spin in the quark model. The connection between the rest frame and infinite momentum frame (light-cone) wave functions and kinematics can be found in ref. [18].

We now check whether it is possible to explain the observed data for Γ^p and Γ^n within the $SU(6)$ naive quark model by taking into account the Melosh-Wigner rotation effect. Though we do not expect this to be the real situation, it is interesting since there existed a general impression that it is impossible to explain the proton spin "puzzle" within the $SU(6)$ naive quark model. Also an early attempt [4] for such purpose failed, by using the early EMC data $\Gamma^p = 0.126$ and Γ^n obtained from the Bjorken sum rule $\Gamma^p - \Gamma^n = \frac{1}{6}G_A/G_V$. We start from the conventional $SU(6)$ naive quark model wave functions for the proton and the neutron

$$|p^{\uparrow}\rangle = \frac{1}{\sqrt{18}}\left(2|u^{\uparrow}u^{\uparrow}d^{\downarrow}\rangle - |u^{\uparrow}u^{\downarrow}d^{\uparrow}\rangle - |u^{\downarrow}u^{\uparrow}d^{\uparrow}\rangle\right) + (\text{cyclic permutation})\,; \qquad (14)$$

$$|n^{\uparrow}\rangle = \frac{1}{\sqrt{18}}\left(2|d^{\uparrow}d^{\uparrow}u^{\downarrow}\rangle - |d^{\uparrow}d^{\downarrow}u^{\uparrow}\rangle - |d^{\downarrow}d^{\uparrow}u^{\uparrow}\rangle\right) + (\text{cyclic permutation})\,. \qquad (15)$$

One finds that the quark spin contributions $\Delta u_{QM} = \frac{4}{3}$, $\Delta d_{QM} = -\frac{1}{3}$, and $\Delta s_{QM} = 0$ for the proton, and the exchange of $u \leftrightarrow d$ in the above quark spin contributions gives those for the neutron. Then we get the integrated spin structure functions for the proton and the neutron as

$$\Gamma^p = \frac{1}{2}\left(\frac{4}{9}\langle M_u\rangle \Delta u_{QM} + \frac{1}{9}\langle M_d\rangle \Delta d_{QM} + \frac{1}{9}\langle M_s\rangle \Delta s_{QM}\right); \qquad (16)$$

$$\Gamma^n = \frac{1}{2}\left(\frac{1}{9}\langle M_u\rangle \Delta u_{QM} + \frac{4}{9}\langle M_d\rangle \Delta d_{QM} + \frac{1}{9}\langle M_s\rangle \Delta s_{QM}\right), \qquad (17)$$

where $\langle M_q\rangle$ is the averaged value of the Melosh-Wigner rotation factor for the quark q. From eqs. (16) and (17) we obtain

$$\langle M_u\rangle \Delta u_{QM} = \frac{24\Gamma^p - 6\Gamma^n - \langle M_s\rangle \Delta s_{QM}}{5}\,; \qquad (18)$$

$$\langle M_d\rangle \Delta d_{QM} = \frac{24\Gamma^n - 6\Gamma^p - \langle M_s\rangle \Delta s_{QM}}{5}\,, \qquad (19)$$

from which we get the values

$$\langle M_u\rangle \Delta u_{QM} = 0.689\,; \qquad (20)$$

$$\langle M_d\rangle \Delta d_{QM} = -0.307\,, \qquad (21)$$

with the inputs $\Gamma^p = 0.136$, $\Gamma^n = -0.03$ [11–13], and $\Delta s_{QM} = 0$. Thus we get, for $\Delta u_{QM} = \frac{4}{3}$ and $\Delta d_{QM} = -\frac{1}{3}$, that

$$\langle M_u\rangle = 0.517, \qquad \langle M_d\rangle = 0.921,$$

and

$$r_{d/u} = \langle M_d\rangle / \langle M_u\rangle = 1.78, \qquad (22)$$

which means that we need a flavor asymmetry between the u and d quarks for the Melosh-Wigner rotation factors to reproduce the observed data Γ^p and Γ^n within the $SU(6)$ naive quark model. The sum of quark helicities in this situation is

$$\Sigma = \langle M_u\rangle \Delta u_{QM} + \langle M_d\rangle \Delta d_{QM} + \langle M_s\rangle \Delta s_{QM} \approx 0.38\,, \quad (23)$$

which is small and far from 1, which is the total quark spin contribution $\Delta u_{QM} + \Delta d_{QM} + \Delta s_{QM}$ to the nucleon spin. We need to point out here that there is no mistake in calling the quark helicity $\Delta q = \langle M_u\rangle \Delta u_{QM}$ the quark spin contribution as commonly accepted in the literature, if one properly understands it from a relativistic viewpoint. But in this case there should be also non-zero contribution to the *relativistic* orbital angular momentum even for the S-wave quarks in the naive $SU(6)$ quark model. Detailed illustrations concerning this point can be found in ref. [9] where the role played by the Melosh-Wigner rotation on the quark orbital angular momentum is studied.

We know that a symmetry between the valence $u(x)$ and $d(x)$ quark distributions would mean $F_2^n(x)/F_2^p(x) \geq \frac{2}{3}$ for the unpolarized structure functions $F_2(x)$ in the whole x region $x = 0 \to 1$, and this has been ruled out by the experimental observation that $F_2^n(x)/F_2^p(x) < 0.5$ at $x \to 1$. This indicates an asymmetry between the $u(x)$ and $d(x)$ valence quark distributions, and such an asymmetry, which can be reproduced in an $SU(6)$ quark-spectator-diquark model [19,20], also implies an asymmetry between the Melosh-Wigner rotation factors for $\langle M_u\rangle$ and $\langle M_d\rangle$ [7]. It is interesting to notice that the asymmetry ratio $r_{d/u} = \langle M_d\rangle/\langle M_u\rangle$ larger than 1 is in the right direction as predicted in the quark-spectator-diquark model [7], though the magnitude is not so big as that given in eq. (22). This may imply that an additional source for a bigger u-d flavor asymmetry is needed for a more realistic description of the nucleon.

3 The intrinsic nucleon sea from the baryon-meson fluctuations

Though the proton spin "puzzle" raised doubt about the quark model at first, there has been a consistent attempt to understand the problem within the quark model framework on extended quark models [3,21,22], and also on the quark model in the light-cone formalism [4–8]. For example, Jaffe and Lipkin [3] found that both the EMC data and the β-decay data can be fitted using a "reasonable modification" of the standard quark model in which the only additional degrees of freedom are a single quark-antiquark pair in the lowest states of spin and orbital motion allowed by conservation laws. Keppler *et al.* [21] pointed out that the $5q$ component should be dominated by pseudoscalar S-wave mesons. Qing, Chen, and Wang [22] gave a numerical calculation of the coefficients of the total wave function in the non-relativistic quark potential model by including the Melosh-Wigner rotation effect [4], although in a different manner, and showed that the proton wave function is dominated by the bare $3q$ state.

In this section, we will perform a more detailed analysis of the spin structure in an extended quark model by taking into account the higher Fock states in the wave function of the proton, and check how these higher Fock states may influence the analysis in sect. 2, where we considered the effect of the Melosh-Wigner rotation with the three valence quark component only. In the higher Fock states, the quark and antiquark of a quark-antiquark pair are rearranged non-perturbatively with the three valence quarks into a meson and a baryon and we write the configuration as a baryon-meson fluctuation. In the "minimal" quark model of Jaffe-Lipkin [3], the quark-antiquark pairs are actually vector mesons in a baryon-meson fluctuation picture. The higher Fock state in the "minimal" quark model, which is referred to as Jaffe-Lipkin term, can be written as

$$|[JL]^{\uparrow}\rangle = \cos\theta|[b\varepsilon]^{\uparrow}\rangle + \sin\theta|[bD]^{\uparrow}\rangle, \quad (24)$$

where b denotes the three-quark qqq component for a bare nucleon. The extra $qqqQ\bar{Q}$ component $|[b\varepsilon]^{\uparrow}\rangle$ with the 0^{++} $Q\bar{Q}$ denoted by ε can be written as

$$|\varepsilon\rangle = \sqrt{\frac{1}{3}}|Y^{\Uparrow}X^{\Downarrow}\rangle + \sqrt{\frac{1}{3}}|Y^{\Downarrow}X^{\Uparrow}\rangle - \sqrt{\frac{1}{3}}|Y^{0}X^{0}\rangle, \quad (25)$$

and the extra $qqqQ\bar{Q}$ component $|[bD]^{\uparrow}\rangle$ with the 1^{++} $Q\bar{Q}$ denoted by D can be written as

$$|[bD]^{\uparrow}\rangle = \sqrt{\frac{2}{3}}|b^{\downarrow}D^{\Uparrow}\rangle - \sqrt{\frac{1}{3}}|b^{\uparrow}D^{0}\rangle, \quad (26)$$

with

$$|D^{\Uparrow}\rangle = \sqrt{\frac{1}{2}}|Y^{\Uparrow}X^{0}\rangle - \sqrt{\frac{1}{2}}|Y^{0}X^{\Uparrow}\rangle; \quad (27)$$

$$|D^{0}\rangle = \sqrt{\frac{1}{2}}|Y^{\Uparrow}X^{\Downarrow}\rangle - \sqrt{\frac{1}{2}}|Y^{\Downarrow}X^{\Uparrow}\rangle, \quad (28)$$

where $D^{\Uparrow}$, D^{0}, and $D^{\Downarrow}$ denote the J_3 states of the $Q\bar{Q}$ pair; $Y^{\Uparrow}$, Y^{0}, and $Y^{\Downarrow}$ denote the L_3 states of the $Q\bar{Q}$ spin; $X^{\Uparrow}$, X^{0}, and $X^{\Downarrow}$ denote the S_3 states of the $Q\bar{Q}$ spin; and $\Uparrow$ denotes a $J_3 = 1$ spin contribution and $\uparrow$ denotes a $J_3 = 1/2$ spin contribution. With the above higher Fock states included, Jaffe and Lipkin found that the proton state has only a small amplitude to be a bare three-quark baryon state, in order to reproduce the large negative sea spin found in their analysis on the hyperon beta decay, baryon magnetic moments and the EMC result on the fraction of the spin of the nucleon carried by the spins of the quarks [3].

In the Jaffe-Lipkin term, only P-wave vector $q\bar{q}$ pairs have been taken into account. However, if we consider the $qqqQ\bar{Q}$ component as a baryon-meson fluctuation of the nucleon, then the dominant fluctuations should be the ones in which the baryon-meson has the smallest off-shell energy [14]. Therefore, energy considerations require that the $qqqQ\bar{Q}$ component should be dominated by pseudoscalar S-wave mesons, like the pion [21]. In order to describe a nucleon state more realistically, we include these new higher Fock states in addition to the Jaffe-Lipkin states, and the nucleon state should be in principle extended to

$$|B^{\uparrow}\rangle = \cos\alpha\cos\beta|b^{\uparrow}\rangle + \sin\alpha\cos\beta|[BM]^{\uparrow}\rangle + \sin\beta|[JL]^{\uparrow}\rangle, \quad (29)$$

where α and β are the mixing angles between the bare baryon state and the baryon-meson states $|[BM]^{\uparrow}\rangle$ and $|[JL]^{\uparrow}\rangle$, and the baryon-meson BM state can be written as

$$|[BM]^{\uparrow}\rangle = \sqrt{\frac{2}{3}}|b^{\downarrow}MY^{\Uparrow}\rangle - \sqrt{\frac{1}{3}}|b^{\uparrow}MY^{0}\rangle, \quad (30)$$

where M denotes the spin contribution from the pseudoscalar meson (with spin zero but parity -1), and Y denotes orbital angular momentum (with $L = 1$) due to the relative motion between the baryon and the meson. We can also extend the BM term by including the $b^* = qqq$ state with spin $S = 3/2$, if higher order baryon-meson fluctuations need to be considered, and in this case we write

$$|[BM]^{\uparrow}\rangle = A(bM)|[bM]^{\uparrow}\rangle + A(b^*M)|[b^*M]^{\uparrow}\rangle, \quad (31)$$

where

$$|[bM]^{\uparrow}\rangle = \sqrt{\frac{2}{3}}|b^{\downarrow}MY^{\Uparrow}\rangle - \sqrt{\frac{1}{3}}|b^{\uparrow}MY^{0}\rangle, \quad (32)$$

as in eq. (30), and

$$|[b^*M]^{\uparrow}\rangle = \sqrt{\frac{1}{2}}|b^{*\Uparrow\uparrow}MY^{\Downarrow}\rangle - \sqrt{\frac{1}{3}}|b^{*\uparrow}MY^{0}\rangle + \sqrt{\frac{1}{6}}|b^{*\downarrow}MY^{\Uparrow}\rangle. \quad (33)$$

The anti-quarks are unpolarized since they exit only in the pseudoscalar meson of the BM state.

Using the wave function (29), we now calculate the contributions Σ_v, Σ_s, and Λ_s, of the valence quark spins,

Table 1. The mixing angles.

$\Sigma_s(\text{II}) = -0.69 \pm 0.27$			$\Sigma_s(\text{III}) = -0.56 \pm 0.22$		
$\sin\alpha$	$\sin\beta$	$\sin\theta$	$\sin\alpha$	$\sin\beta$	$\sin\theta$
$\pm\, 0.200$	$1.080^{-0.281}_{+0.258}$	$-\,0.408^{-0.112}_{+0.058}$	$\pm\, 0.200$	$0.947^{-0.086}_{+0.117}$	$-\,0.452^{+0.144}_{-0.105}$
$\pm\, 0.400$	$1.065^{-0.243}_{+0.198}$	$-\,0.429^{-0.019}_{+0.008}$	$\pm\, 0.400$	$0.956^{-0.220}_{+0.179}$	$-\,0.436^{-0.023}_{+0.010}$
$\pm\, 0.600$	$1.052^{-0.180}_{+0.166}$	$-\,0.452^{+0.086}_{-0.042}$	$\pm\, 0.600$	$0.966^{-0.146}_{+0.143}$	$-\,0.419^{+0.097}_{-0.050}$
$\pm\, 0.800$	$1.041^{-0.125}_{+0.159}$	$-\,0.472^{+0.155}_{-0.098}$	$\pm\, 0.800$	$0.975^{-0.086}_{+0.117}$	$-\,0.405^{+0.144}_{-0.105}$

the spin of the sea, and the orbital angular momentum of the sea, to the spin of the proton, and we obtain

$$\Sigma_v = \cos^2\alpha\cos^2\beta - \frac{1}{3}\sin^2\alpha\cos^2\beta + \sin^2\beta\cos^2\theta - \frac{1}{3}\sin^2\beta\sin^2\theta; \qquad (34)$$

$$\Sigma_s = \frac{8}{3}\sqrt{\frac{1}{2}}\sin^2\beta\sin\theta\cos\theta + \frac{2}{3}\sin^2\beta\sin^2\theta; \qquad (35)$$

$$\Lambda_s = -\frac{8}{3}\sqrt{\frac{1}{2}}\sin^2\beta\sin\theta\cos\theta + \frac{2}{3}\sin^2\beta\sin^2\theta + \frac{4}{3}\sin^2\alpha\cos^2\beta, \qquad (36)$$

with

$$\Sigma_v + \Sigma_s + \Lambda_s = 1. \qquad (37)$$

We can say alternatively that Σ_v comes from the spin sums of all $b = qqq$ terms, Σ_s from the spin sums of all $Q\bar{Q}$ terms (X terms in the Jaffe-Lipkin term and M terms in the BM term eq. (30)), and Λ_s from the orbital angular momentum of all Y terms in the nucleon state $|B^{\uparrow}\rangle$.

It can be easily seen that the sea spin Σ_s comes entirely from the Jaffe-Lipkin term, since the spin contribution from the M terms is zero. It is also interesting that Σ_s cannot be negative if there is no interference between the two components $|b\varepsilon\rangle$ and $|bD\rangle$ in the Jaffe-Lipkin term eq. (24). If we follow ref. [3] and adopt the two models for the sea spin Σ_s, then we find that we must arrive at the conclusion of Jaffe-Lipkin term dominance. In the first model (called II in ref. [3]), the sea is taken as $SU(3)_{\text{flavor}}$ symmetric, and $\Sigma_s(\text{II}) = -0.69 \pm 0.27$. In the second model (called III in ref. [3]), the sea is taken as $SU(2)_{\text{flavor}}$ symmetric, and $\Sigma_s(\text{III}) = -0.56 \pm 0.22$. On the other hand, the data on hyperon and nucleon β-decays requires Σ_v to be approximately $\frac{3}{4}$. Of course, it is impossible for us to completely determinate α, β and θ using the values of Σ_v and Σ_s mentioned above. But, taking (34) and (35) as constraint conditions, we can give a range of values of these mixing angles. Selected values of mixing angles are shown in table 1. Notice that we get values of $\sin\beta$ larger than 1, as was also the situation in the Jaffe-Lipkin analysis [3], but physical values $|\sin\beta| < 1$ are allowed within error bars. The results in table 1 show that a physically reasonable $\cos\beta$ can only have a very small value with the above Σ_v and Σ_s, and this requires the Jaffe-Lipkin term dominance. The sea in the baryon-meson state (30) only provides the orbital angular momentum to the nucleon, and the Jaffe-Lipkin term (24) provides the negative-polarized sea spin. Thus, the necessity of the Jaffe-Lipkin term depends only on the sea quark polarization of the nucleon.

From a strict sense, the sea spin Σ_s has not been measured directly, and also the Melosh-Wigner rotation factors should be introduced into the so-called spin term Σ_v obtained from hyperon and nucleon β-decays, and the flavor asymmetry and $SU(3)$ symmetry breaking should be important. Therefore, the above analysis needs to be updated. It would be more practical to decompose the spin by the contributions from the quarks $\Sigma_q = \Sigma_v + \frac{1}{2}\Sigma_s$, the antiquarks $\Sigma_{\bar{q}} = \frac{1}{2}\Sigma_s$, and the orbital angular momentum Λ_s, which still meet the condition

$$\Sigma_q + \Sigma_{\bar{q}} + \Lambda_s = 1. \qquad (38)$$

The antiquark helicity distributions extracted from semi-inclusive deep inelastic scattering experiments are consistent with zero [23], in agreement with the small antiquark polarization predicted in both the baryon-meson fluctuation model [14] and a chiral quark model [24]. There is still no direct evidence for a large negative antiquark polarization in experiments. We also point out here that there should be a quark-antiquark asymmetry for the spin of the sea when flavor decomposition is necessary [14].

Since new measurements on the polarized structure functions for both the proton and the neutron have become available, we will use the measured Γ^p and Γ^n as inputs to study the effects due to the Melosh-Wigner rotation, by including also the effects due to Jaffe-Lipkin and BM higher Fock state terms in the nucleon wave function. Another aspect that we need to take into account is that the u and d flavor asymmetries should exist in both the valence and sea contents of the nucleon. The observation of the Gottfried sum rule violation in several processes [15,16] implies that there is an important contribution coming from the lowest baryon-meson fluctuation $p(uudD\bar{D}) = n(udD)\pi^+(u\bar{D})$ of the proton [14,25]. This puts a constraint on the value of α for the BM mixing term. If one assumes an isospin symmetry between the proton and neutron [26], then the Gottfried sum rule violation implies an asymmetry between the u and d sea distributions inside the proton

$$\int_0^1 \mathrm{d}x \left[\bar{d}(x) - \bar{u}(x)\right] = 0.148 \pm 0.039. \quad (39)$$

If we consider only the $p(uudD\bar{D}) = n(udD)\pi^+(u\bar{D})$ component inside the BM term and neglect flavor asymmetry in the Jaffe-Lipkin term, then we get the constraint

$$\sin^2\alpha \cos^2\beta = 0.148. \quad (40)$$

The u and d quark spins in the proton wave function should be

$$\Delta u_{QM} = \cos^2\alpha\cos^2\beta\Delta u_0 - \frac{1}{3}\sin^2\alpha\cos^2\beta\Delta d_0 + \sin^2\beta\Delta u_{JL}; \quad (41)$$

$$\Delta d_{QM} = \cos^2\alpha\cos^2\beta\Delta d_0 - \frac{1}{3}\sin^2\alpha\cos^2\beta\Delta u_0 + \sin^2\beta\Delta d_{JL}, \quad (42)$$

where $\Delta u_0 = 4/3$ and $\Delta d_0 = -1/3$ are the u and d quark spins for the bare qqq proton, and Δu_{JL} and Δd_{JL} are the u and d quark spins for the Jaffe-Lipkin term eq. (24) from b, ε, and D

$$\Delta q_{JL} = \left(1 - \frac{4}{3}\sin^2\theta\right)\Delta q_0 + \frac{1}{4}\Sigma_s \quad (43)$$

for $q = u, d$ in case of only charge neutral $Q\bar{Q}$'s with u and d flavors. Substituting the above Δu_{QM} and Δd_{QM} into eqs. (20) and (21), we get

$$\langle M_u\rangle = 0.598\,, \qquad \langle M_d\rangle = 0.878\,,$$

and

$$r_{d/u} = \langle M_d\rangle/\langle M_u\rangle = 1.47\,, \quad (44)$$

for $\beta = 0$ without the Jaffe-Lipkin term. We find that the u and d flavor asymmetry $r_{d/u}$ is reduced compared to eq. (22) and this shows that the $p(uudD\bar{D}) = n(udD)\pi^+(u\bar{D})$ fluctuation produces a more reasonable d/u Melosh-Wigner rotation asymmetry than in the naive picture with the bare nucleon state of only three valence quarks [7]. This $\beta = 0$ example shows that we can have a scenario of zero antiquark polarization while explaining all the data. Therefore the Melosh-Wigner rotation changes the previous conclusion of Jaffe-Lipkin dominance, allowing for small values of β.

In fact, we should also include other baryon-meson fluctuations in a more realistic picture of intrinsic sea quarks [14], such as $p(uudU\bar{U}) = \Delta^{++}(uuU)\pi^-(d\bar{U})$ for the intrinsic $U\bar{U}$ quark-antiquark pairs and $p(uudS\bar{S}) = \Lambda(udS)K^+(u\bar{S})$ for the intrinsic strange quark-antiquark pairs. In this case we can write the baryon-meson term as

$$\sin\alpha\cos\beta\left|[BM]^\uparrow\right\rangle = A(n\pi^+)\left|n\pi^+\right\rangle + A(\Lambda K^+)\left|\Lambda K^+\right\rangle + A(\Delta^{++}\pi^-)\left|\Delta^{++}\pi^-\right\rangle, \quad (45)$$

where we take the baryon-meson configuration probabilities $P(p = BM) = [A(BM)]^2$ as

$$P(p = n\pi^+) \sim 15\%\,; \qquad P(p = \Lambda K^+) \sim 3\%\,; \qquad P(p = \Delta^{++}\pi^-) \sim 1\%\,, \quad (46)$$

as estimated from a reasonable physical picture [14]. With the above baryon-meson fluctuations considered, we find,

$$\langle M_u\rangle = 0.624\,, \qquad \langle M_d\rangle = 0.912\,,$$

and

$$r_{d/u} = \langle M_d\rangle/\langle M_u\rangle = 1.46\,, \quad (47)$$

which are close to eq. (44), the case with only $p = n\pi^+$ fluctuation. Thus our above analysis supports a reasonable picture of a dominant valence three-quark component with a certain amount of the energetically favored baryon-meson fluctuations [14], as a "minimal" quark model for the spin relevant observations in DIS processes and also for several phenomenological anomalies related to the flavor content of nucleons [14]. Of course, we can also include the necessary other higher $5q$ Fock states approximated in terms of the BM state and the Jaffe-Lipkin state.

The gluon distribution of a hadron is usually assumed to be generated from the QCD evolution. However, it has been pointed in ref. [27] that there exist intrinsic gluons in the bound-state wave function. Therefore, we could also consider the possibility of including a $(qqqg)$ Fock state in our description. Unfortunately, the gluon is always a relativistic particle, and it is not easy to incorporate it in the present framework. We must use a relativistic approach from the start, such as the one given in ref. [28].

4 Summary and discussion

We investigated the spin structure of the nucleon in a simple quark model. First, we studied the effect due to the Melosh-Wigner rotation. We found that an introduction of an up-down quark flavor asymmetry in the Melosh-Wigner rotation factors can reproduce the present experimental data of the integrated spin structure functions for both the proton and the neutron within a simple $SU(6)$ quark model with only three valence quarks. And then, we discussed the contributions to the nucleon spin from various components of the nucleon wave function. The calculated results indicate that the baryon-meson state of Jaffe-Lipkin with vector meson is only necessary when the sea quarks (or more definitely, the antiquarks) are negatively polarized, regardless of the existence of states which include the pseudoscalar mesons.

The Melosh-Wigner rotation is one of the most important ingredients of the light-cone formalism. Its effect is of fundamental importance in the spin content of hadrons, and it is mainly due to the transverse momentum of quarks in the nucleon. Actually, it reflects some relativistic effects of a quark system. On the other hand, the simple quark model discussed here includes the baryon-meson fluctuations in the nucleon wave function, which is a non-perturbative effect. The present investigation shows that relativistic and non-perturbative effects are very important in order to understand the spin structure of the nucleon. In the simple quark model, the bare three-quark component and the baryon-meson state with a pesudoscalar meson, are still dominant concerning the proton spin problem in polarized structure functions, after we take into account the Melosh-Wigner rotation effect. Thus, we arrive at a new "minimal" quark model, which is close to the naive quark model, to understand the proton spin "puzzle" or "crisis".

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