Comments on Lattice Calculations of Proton Spin Components

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Abstract

Comments on the recent lattice QCD calculations of the flavor-singlet axial coupling constant $g_A^0$ and individual quark and gluon spin contributions to the proton spin is given. I point out the physics learned from these calculations as well as some of the lessons and pitfalls.
Recent experiments on polarized deep inelastic lepton-nucleon scattering from SMC [1] and E143 [2] have confirmed the finding of the earlier EMC [3] results that the flavor-singlet $g_A^0$ is small [4]. In the deep inelastic limit, the integral of the polarized structure function is related to the forward matrix elements of axial currents from the operator product expansion [5]. Combined with the neutron and hyperon decays, the flavor-singlet axial coupling $g_A^0$ is extracted. Since the axial current is the canonical spin operator, $g_A^0$ is thus the quark spin content of the nucleon; i.e. $g_A^0 = \Delta u + \Delta d + \Delta s$, where the spin content $\Delta q (q = u, d, s)$ is defined in the forward matrix element of the axial current, $\langle ps|\bar{q}i\gamma_\mu\gamma_5q|ps\rangle = 2MNs_\mu\Delta q$.

The fact that $g_A^0$, which represents the quark spin contribution to the proton spin, is found to be much smaller than the expected value of unity from the non-relativistic quark model or 0.75 from the SU(6) relation ($3/5$ of the isovector coupling $g_3^A = 1.2574$) has surprised physicists who have taken the valence quark model for granted. In view of the exciting puzzle presented by the experiment, the gross failure of the valence quark model, and its possible manifestation of the axial anomaly besides $\pi^0 \rightarrow \gamma\gamma$, several lattice QCD calculations were carried out in the last 6 years as an attempt to meet the challenge of explicating the phenomenon directly from QCD.

In the following, I shall summarize the progress that has been made in this direction and point out the pitfalls and/or shortcomings in each of the calculations reviewed here. There are three approaches to address the issue of the proton spin components. The first is the calculation of the gluon spin content, the second is the calculation of the axial anomaly, and the third is the calculation of the quark spin content from the axial-vector current.

1 Gluon Spin Content

Ref [6]: Jeffrey E. Mandula, “Lattice Simulation of the Anomalous Gluon Contribution to the Proton Spin”, Phys. Rev. Lett. 65, 1403 (1990).

This is the first attempt [6] to calculate the gluon spin content as a way of understanding the EMC experiment.

1.1 Calculational details

- Lattice parameters: 204 $6^3 \times 10$ lattice at $\beta = 5.7$ and the Wilson mass parameter $\kappa = 0.162$.

- This a quenched approximation (without dynamical fermion loops) with lattice spacing $a \sim 1.0 GeV^{-1}$.

- The gluon spin operator is the lattice version of the anomalous current.

$$K_\mu = \epsilon_{\mu\nu\lambda\rho}TrA^\nu(G^{\lambda\rho} - 2/3 A^{\lambda}A^\rho)$$ (1)
which is a particular case of the Chern-Simons form [7]. The gluon spin fraction is defined as
\[ \langle ps|K_\mu|ps \rangle = 2M_N s_\mu \Delta g. \] (2)

- Since the current is not gauge invariant, the calculation is done in the \( A_4 = 0 \) gauge where the second term in \( K_i \) (\( i = 1,2,3 \)) vanishes.

- It turns out that the signal is very noisy and only an upper bound is given, i.e. \( \Delta g \leq |0.5| \). Since the original motivation of the work is to evaluate the possible gluon spin mixture in the quark axial-current matrix element via the triangle diagram [8, 9, 10], the author gives the upper limit of the mixture \((3\alpha_s/2\pi)|\Delta g| \leq 0.05\).

1.2 Comments

- This work has drawn several comments:
  Efremov, Soffer, and Törnqvist [11] assert that what is calculated in [6] contains a contribution from the “ghost” pole. On the other hand, Manohar [13] points out that even in the forward direction, \( \Delta g \) may still depend on the gauge direction \( \eta \). Mandula replies [12] that “while gauge-variant singularities and \( \eta \) dependence are kinematically allowed in the forward matrix element \( \langle ps|K_\mu|ps \rangle \), they are not expected to occur, on either dynamical, symmetry, or invariance grounds.”

- We believe that the issue of “ghost” pole is a red herring. The “ghost” was invented by Veneziano [17] for the convenience of taking care of a minus sign in the topological susceptibility which may well come from a contact term. Unlike the claim of Efremov, Soffer, and Törnqvist that “This ghost pole is necessary for the resolution of the U(1) problem in QCD”, Witten’s resolution of the U(1) problem in terms of the topological susceptibility does not depend on the “ghost”. Furthermore, it has been shown [18] that one can adapt Veneziano’s approach without invoking the “ghost”. On the other hand, Manohar does have a point, especially in view of the fact that it has been shown by Cronström and Mickelsson [14] that under gauge transformations,

\[ K_\mu \longrightarrow K_\mu + 2\varepsilon_{\mu\alpha\beta}\partial^\alpha Tr A^\alpha U^{-1} \partial^\beta U + \partial^\alpha H_{\mu\nu}(U). \] (3)

The last term is not sensitive to the local deformation of \( U \) and can be considered a topological current. For large gauge transformation where the topological (or instanton) number changes, the forward matrix element
\[ \lim_{q \to 0} \langle p + q|\partial^\alpha H_{\mu\nu}(U)|p \rangle = \lim_{q \to 0} iq^\alpha \langle p + q|H_{\mu\nu}(U)|p \rangle \] (4)
does not vanish [15, 16]. Thus the calculation of the gluon spin content using the anomalous current in eq. (1) is gauge-dependent even for forward matrix element.

- It turns out that in the temporal axial gauge, \( A_4 = 0 \), the anomalous current \( K_i \) in eq. (1) coincides with the gluon spin operator \( 2Tr(A \times E)^i \) [15]. Hence, modulo gauge-dependence, what is calculated in [6] is the gluon spin content.
2 Flavor-Singlet $g_A^0$ from Axial Anomaly

In this approach, one calculates the following matrix element

$$A = \lim_{q \to 0} \frac{i |s|}{q_s} \langle p, s | N_f \frac{\alpha_s}{2\pi} G^{a}_{\mu\nu} \tilde{G}^{a\mu\nu} | p', s \rangle.$$  \hspace{1cm} (5)

The basis for calculating $A$ instead of the matrix element of the axial current directly can be seen as follows. Inserting the anomalous Ward identity

$$\partial^\mu A^0_{\mu} = 2 \sum_{f=1}^{N_f} m_f \bar{u}_f i \gamma_5 q_f + N_f \frac{\alpha_s}{2\pi} G^{a}_{\mu\nu} \tilde{G}^{a\mu\nu},$$

between proton states, one obtains

$$\overline{\pi}(p) i \gamma_5 u(p') [2M g_A^0(q^2) + q^2 H_A^0(q^2)] = \langle p | 2mP + 2N_f q | p' \rangle,$$

where $P$ is the pseudoscalar current, i.e. $mP = \sum_{f=1}^{N_f} m_f \bar{u}_f i \gamma_5 q_f$ and $q$ is the topological charge operator, $q = (\alpha_s/4\pi)G^{a}_{\mu\nu} \tilde{G}^{a\mu\nu}$.

Since there is no Goldstone pole at the chiral limit in the U(1) channel, one can take the $q^2 \to 0$ and the $m \to 0$ limits and drops the $h_A$ and $P$ terms in eq. (7) to obtain

$$g_A^0 = \Delta \Sigma = A$$  \hspace{1cm} (8)

Thus one can calculate the matrix element of the axial anomaly to obtain $\Delta \Sigma$. One will not be able to calculate $\Delta u, \Delta d,$ and $\Delta s$ separately in this approach though.

2.1 Quenched Approximation

2.1.1 Two calculations

1. Ref [13]: B. Allés, M. Campostrini, L. Del Debbio, A. Di Giacomo, H. Panagoulos, and E. Vicari, “The Proton Matrix Element of the Topological Charge in Quenched QCD”, Phys. Lett. B336, 248 (1994).

   - Lattice parameters: 100 $16^3 \times 32$ lattice at $\beta = 6.0$. Smear source for the nucleon in the Coulomb gauge. Wilson hopping parameters $\kappa = 0.153, 0.154, 0.155$ are used for the quark propagators.
   - Nonperturbative method is used to determine the finite lattice renormalization constant.
   - The signal is zero within errors. An upper bound of the matrix element $A$ in eq. (7) is set to be 0.4.
2. Ref [20]: R. Gupta and J.E. Mandula, “Matrix Elements of the Singlet Axial Vector Current in the Proton”, Phys. Rev. D50, 6931 (1994).

- Lattice parameters: 35 $16^3 \times 40$ lattice at $\beta = 6.0$. The quark masses used are $\kappa = 0.154$ and 0.155, corresponding to pions of mass 700 and 560 MeV, respectively. The Wuppertal source is used for the nucleon, hence it is a gauge invariant calculation.

- Again, the authors found that the data are statistically indistinguishable from zero.

### 2.1.2 Comments

- Irrespective of the fact that no signal is seen in these calculations, it is pointed out emphatically by Gupta and Mandula [20] that this approach which relies on the use of the axial anomaly fails in the quenched approximation. This can be see as follows. What is derived in eq. (8) depends on the fact that there is no massless Goldstone mode in the U(1) channel at the chiral limit. However, this is not realized in the QUENCHED approximation where the would be Goldstone bosons are present. It is clearly seen in the study of the anomalous Ward identity for $g_A^0$ [18] that the induced pseudoscalar form factor $h_A$ has a pole structure $\frac{1}{q^2 - m_{\eta_0}^2}$ where $m_{\eta_0}$ is the would-be Goldstone meson mass, while the pseudoscalar current $2m_P$ has a pole structure $\frac{m_{\eta_0}^2}{q^2 - m_{\eta_0}^2}$. Combined, they give the structure $\frac{q^2 - m_{\eta_0}^2}{q^2 - m_{\eta_0}^2}$ which tends to unity at the $q^2 \to 0$ and $m \to 0$ limits. In other words, in the quenched approximation, $g_A^0$ is not simply related to $A$ as in eq. (8). The pseudoscalar current $2m_P$ also contributes in this case even in the chiral limit as is in the Goldberger-Treiman relation.

- Gupta and Mandula [20] further suggest that due to the presence of the double/single would-be Goldstone pole in the pseudoscalar current /axial anomaly, the result from the quenched approximation diverges at the chiral limit and thus one will not be able to utilize the anomalous Ward identity to calculate $g_A^0$. Fortunately, it can be seen from our earlier study [18] that the double pole in the pseudoscalar current cancels the single pole from the axial anomaly. This is due to the fact that the topological susceptibility vanishes at the chiral limit so that the vacuum has no $\theta$ dependence. Furthermore, the remaining single would-be Goldstone pole (at $q^2 = 0$) will be cancelled by the quark mass in the pseudoscalar current $2m_P$. Thus every term in the expression of eq. (8) is finite in the chiral limit of the quenched approximation. We conclude that one can still utilize the anomalous Ward identity in the quenched approximation, provided the pseudoscalar current is evaluated in addition to the axial anomaly term.
2.2 Calculation with Dynamical Fermions

Ref. [21]: R. Altmeyer, M. Göckler, R. Horsley, E. Laermann, and G. Schierholz, “Axial Baryonic Charge and the Spin Content of the Nucleon: a Lattice Investigation”, Phys. Rev. D49, R3087 (1994).

2.2.1 Calculational Details

- Lattice parameters: $16^3 \times 24$ dynamical fermion lattice at $\beta = 5.35$ with four flavors of staggered fermions with mass $ma = 0.01$. 85 gauge configurations separated by 5 trajectories are used. The lattice spacing determined by the $\rho$ mass is 0.14 fm.
- The result of eq. (5) calculated at $|\vec{q}| \sim 500$ MeV gives $A = 0.18 \pm 0.02$ which the authors identify with $\Delta \Sigma$ through eq. (8).

2.2.2 Comments

- This is the first calculation which uses the dynamical fermion gauge configurations and actually sees a signal which is quite commendable. Moreover, the result agrees with the experimental finding.
- However, this calculation is done at finite q and finite quark mass m. As we alluded to earlier, the induced pseudoscalar form factor $h_A$ will contribute at finite q (NB. eq. [9]) and the pseudoscalar current $2mP$ will contribute at finite m. As long as the quark mass (in both the valence and the fermion loops) and the momentum transfer q are not extrapolated to 0, the relation in eq. (8) will always be subjected to these systematic errors. In this approach, one can not separately calculate $\Delta u$, $\Delta d$, and $\Delta s$. Furthermore, just knowing $g_A^0$ through the matrix element of the anomaly does not teach us why $g_A^0$ is as small as it.

3 Quark Spin Content from the Axial-Vector Current

This is the direct way of calculating the quark spin content, since it is defined by the forward axial current matrix element and one can calculate it flavor by flavor. The only problem is that in addition to the connected insertion, there is a disconnected insertion. The disconnected insertion requires the calculation of quark loops which is prohibitively time-consuming if one is to invert the whole quark matrix directly. This is the reason why earlier attempts were made to calculate the axial anomaly in order to circumvent this numerical difficulty. It turns out that there have been three calculations which tackle this problem with different numerical techniques.
3.1 Quark Loops in a Smaller Box

Ref. [22]: Jefferey E. Mandula and Michael C. Ogilvie, “A New Technique for Measuring the Strangeness Content of the Proton on the lattice”, Phys. Lett. B312, 327 (1993).

3.1.1 Technical Details

- Lattice parameters: 16 $16^3 \times 24$ quenched lattice at $\beta = 5.7$. The valence quark masses are about 0.6, 0.2, and 0.1 GeV corresponding to Wilson $\kappa = 0.140, 0.160, \text{and } 0.164$. The strange mass in the loop is about 0.16 GeV ($\kappa = 0.162$).

- The quark propagator for the loop is calculated in a $9^4$ box and the loop is evaluated on a time slice for every other site in each spatial direction. This saves a factor $\sim 500$ in computer time comparing to the straight forward calculation and thus makes the project feasible.

- $\Delta s$ tends to be negative for light valence quarks in the nucleon. However, no plateau is reached to give a final result.

3.1.2 Comments

This technique should work. The devil is in the statistics.

3.2 Volume Source Technique

Ref. [24]: M. Fukugita, Y. Kuramashi, M. Okawa, and A. Ukawa, “Proton Spin Structure from Lattice QCD”, Phys. Rev. Lett. 75, 2092 (1995).

3.2.1 Technical Details and Results

- Lattice parameters: $260 16^3 \times 20$ quenched lattice at $\beta = 5.7$. The Wilson hopping parameters $\kappa = 0.160, 0.164, \text{and } 0.1665$ are used. The strange quark corresponds to $\kappa = 0.160$.

- The quark loops are calculated with the volume source technique [23] which relies on the cancellation of gauge non-invariant part through gauge averaging. The time slice from which the nucleon source emerges is fixed in Coulomb gauge.

- The results are summarized in the following table.

3.2.2 Comments

- The result of $\Delta \Sigma$ agrees with experiments well and its smallness is understood as due the sea-quarks which give negative contributions to $\Delta \Sigma$. 
Table 1: Quark spin contents of the proton form the volume source calculation

|                | Value       |
|----------------|-------------|
| $g_A^3(\Delta \Sigma)$ | 0.18(10)    |
| $g_A^3$         | 0.985(25)   |
| $\Delta u$     | 0.638(54)   |
| $\Delta d$     | -0.347(46)  |
| $\Delta s$     | -0.109(30)  |
| $F_A$           | 0.382(18)   |
| $D_A$           | 0.607(14)   |
| $F_A/D_A$       | 0.629(33)   |

- $g_A^3$, $F_A$, and $D_A$ are smaller than the experiments by $\sim 25\%$. Possible sources of systematic errors include the scaling violation effect due to a fairly large lattice spacing [24] and the fitting procedure with the ratio method which can give a jackknife bias of $\sim 10\%$ as compared to the more desirable simultaneous fitting procedure [25].

- Since the time slice from which the nucleon source emerges is fixed to the Coulomb gauge, the results are gauge dependent. Furthermore, the quark current operator $A_{\mu}$ can mix with the gauge non-invariant anomalous current $K_{\mu}$ in eq. (1), a problem déjà vu. To see this, one can construct the lattice version of $K_{\mu}$ with staples in such a way that their ends touch the time slice which is gauge fixed or use the version given by Mandula [6] with the sandwiching U-links lie in the gauge-fixed time slice. These $K_{\mu}$ matrix elements do not vanish on this lattice and become a part of the results obtained in this work. It is then necessary to disentangle this gluon spin contribution from the quark spin part before addressing the proton spin components.

3.3 Stochastic Estimation with $Z_2$ Noise

Ref. [26]: Shao-Jing Dong, Jean-Francois Lagaë, and Keh-Fei Liu, “Flavor-Singlet $g_A^0$ from Lattice QCD”, Phys. Rev. Lett. 75, 2096 (1995).

3.3.1 Technical Details and Results

- Lattice parameters: $24/50 \times 16^3 \times 24$ quenched lattice configurations at $\beta = 6.0$ for the connected/disconnected insertion. The Wilson hopping parameters are $\kappa = 0.148, 0.152, \text{ and } 0.154$. The strange quark corresponds to $\kappa = 0.154$.

- No gauge-fixing is done. Hence the calculation is gauge invariant. The quark loops are calculated by the stochastic method with the optimal $Z_2$ noise [25] which is shown to give the correct answers for the forward matrix elements of the vector and pseudoscalar currents [26].
• Finite $ma$ correction for the quark loops of the Wilson fermion is taken into account [27].

• The results are summarized in the following table.

Table 2: Axial coupling constants and quark spin contents of proton in comparison with experiments

|                  | This Work | Experiments |
|------------------|-----------|-------------|
| $g_0^A = \Delta u + \Delta d + \Delta s$ | 0.25(12)  | 0.22(10) [1] / 0.27(10) [2] |
| $g_3^A = \Delta u - \Delta d$            | 1.20(10)  | 1.2573(28)  |
| $g_8^A = \Delta u + \Delta d - 2\Delta s$| 0.61(13)  | 0.579(25) [29] |
| $\Delta u$    | 0.79(11)  | 0.80(6) [1] / 0.82(6) [2] |
| $\Delta d$    | -0.42(11) | -0.46(6) [1] / -0.44(6) [2] |
| $\Delta s$    | -0.12(1)  | -0.12(4) [1] / -0.10(4) [2] |
| $F_A = (\Delta u - \Delta s)/2$         | 0.45(6)   | 0.459(8) [29] |
| $D_A = (\Delta u - 2\Delta d + \Delta s)/2$| 0.75(11)  | 0.798(8) [29] |
| $F_A/D_A$     | 0.60(2)   | 0.575(16) [29] |

3.3.2 Comments

• This calculation is gauge-invariant in that no gauge-fixing is applied. Since there is no gauge-invariant dimension-three axial operator for the gluon spin as we discussed earlier [14, 15], these results are not mixed with the gluon spin. Only the quark spin content contributes.

• The physical picture of $g_0^A$ is starting to come in view. The smallness of the quark spin content compared to the non-relativistic value of unity is, first of all, due to the fact that the combined relativistic effect and polarization of the cloud-quarks reduces the connected insertion to $0.62 \pm 0.09$, a value very close to $g_8^A$, i.e. $g_{A, \text{con}}^0 \simeq g_8^A$. This is because the disconnected insertion is almost independent of the flavors $u, d,$ and $s$. Furthermore, the sea-quark polarization is large and in the opposite direction of the proton spin. It is the sum of all these effects that produces a small $g_0^A$.

• It is interesting to observe that the sea-quark spin contribution is independent of the quark mass in the loop within errors. This is reminiscent of the $\gamma_5$ current in the context of the topological charge and susceptibility. It is suggestive of the importance of the zero modes and the instantons.

• Albeit the results all agree with experiments, the systematic errors due to the finite volume, discretization, renormalization, and quenched approximation (which could be as large as $7\% - 20\%$ [31]) need to be addressed before a final precise comparison with experiments can be made.
3.4 Moments of Polarized Structure Functions

Ref. [31]: M. Göckler, R. Horseley, E.-M. Ilgenfritz, H. Perlt, P. Rakow, G. Schierholz, and A. Schiller, “Polarized and Unpolarized Nucleon Structure Functions from Lattice QCD”, DESY 95-128, hep-lat/9508004.

3.4.1 Technical Details

- Lattice parameters: 400 – 1000 16$^3 \times 32$ quenched lattice configurations at $\beta = 6.0$. The hopping parameters are $\kappa = 0.1515, 0.153, \text{ and } 0.155$.

- $g_A^3 = 1.07(9)$, the connected insertion part of $g_A^0$ is $0.59(5)$. The $g_1$ sum rule is $0.166(16)$ for the proton and $-0.008(09)$ for the neutron.

3.4.2 Comments

- The results are from the connected insertion only. They have very high statistics. The results on the disconnected insertions are forth-coming.

4 Future

So far, the lattice calculation is only beginning to shed some light on the quark spin content part of the proton spin. We need to calculate the orbital angular momentum and the gluon spin in order to complete the picture of the proton spin composition. In the future, the gauge invariant calculation of the axial-vector matrix elements to address the infinite volume and continuum limits and the dynamical fermions is needed to study the systematic errors of the quark spin content.

This work is partially supported by DOE Grant DE-FG05-84ER40154.

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