Progress in resolving charge symmetry violation in nucleon structure

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Recent work unambiguously resolves the level of charge symmetry violation in moments of parton distributions using 2+1−flavor lattice QCD. We introduce the methods used for that analysis by applying them to determine the strong contribution to the proton-neutron mass difference. We also summarize related work which reveals that the fraction of baryon spin which is carried by the quarks is in fact structure-dependent rather than universal across the baryon octet.

Keywords: Charge symmetry, lattice QCD, parton distributions, isospin.

1. Introduction

Charge symmetry, the equivalence of the u quark in the proton and the d in the neutron, and vice versa, is an excellent approximation in nuclear and hadronic systems — typically respected at ∼1% precision.1–3 Current deep inelastic scattering measurements are such that this level of precision has not yet been reached, with current bounds on charge symmetry violation (CSV) in parton distributions in the range 5-10%.4 Such possibly large CSV effects are of particular interest in the context of a new program at Jefferson Laboratory5 which aims to measure the electron-deuteron parity-violating deep inelastic scattering (PVDIS) asymmetry to better than 1% precision. This would offer an improvement of roughly an order of magnitude over early SLAC measurements,6 with the potential to constitute an important new test of the Standard Model. Reaching this goal will rely on a precise control of strong interaction processes. CSV is likely to be the most significant hadronic uncertainty at the kinematics typical of the JLab program.7–9 Phenomenological studies suggest that CSV could cause ∼1.5 – 2% variations in the PVDIS asymmetry.4 This is sufficient to dis-
guise any signature of new physics, such as supersymmetry, expected to appear at the 1% level.\textsuperscript{10}

Here we review our recent work\textsuperscript{11} which has determined the CSV moments of parton distributions from lattice QCD. Our results, based on 2+1-flavor lattice QCD simulations,\textsuperscript{12,13} reveal $\sim 0.20 \pm 0.06\%$ CSV in the quark momentum fractions. This corresponds to a $\sim 0.4 - 0.6\%$ correction to the PVDIS asymmetry. This precision represents an order of magnitude improvement over the phenomenological bounds reported in Ref.\textsuperscript{4}. This result also constitutes an important step towards resolving the famous NuTeV anomaly.\textsuperscript{14,15} Whereas the original report of a 3-sigma discrepancy with the Standard Model was based on the assumption of negligible CSV, effects of the magnitude and sign reported here act to reduce this discrepancy by one sigma. Similar results for spin-dependent parton CSV suggest corrections to the Bjorken sum rule\textsuperscript{16} at the half-percent level which could possibly be seen at a future electron collider.\textsuperscript{17}

In Section 2 we introduce the techniques used for our calculation in the context of the octet baryon mass splittings.\textsuperscript{18} Section 3 summarizes our parton CSV results, presented in full in Ref.\textsuperscript{11}. Related work which reveals that the fraction of baryon spin which is carried by the quarks is in fact structure-dependent rather than universal across the baryon octet\textsuperscript{19} is highlighted in Section 4.

2. Baryon mass splittings

Charge symmetry refers to the invariance of the strong interaction under a $180^{\circ}$ rotation about the ‘2’ axis in isospin space. At the parton level this invariance implies the equivalence of the $u$ quark in the proton and the $d$ quark in the neutron, and vice-versa. The symmetry would be exact if

- the up and down quarks were mass degenerate: $m_u = m_d$
- the quark electromagnetic charges were equal: $Q_u = Q_d$.

Of course, both of these conditions are broken in nature. This breaking manifests itself, for example, as mass differences between members of baryon isospin multiplets. While these differences have been measured extremely precisely experimentally,\textsuperscript{20} the decomposition of these quantities into strong (from $m_u \neq m_d$) and electromagnetic (EM) contributions is much less well known. Phenomenological best estimates come from an application of the Cottingham sum rule\textsuperscript{21} which relates the electromagnetic baryon self-energy to electron scattering observables. Walker-Loud, Carlson & Miller (WLCM) have recently revised the standard Cottingham formula;\textsuperscript{22} noting that two
Lorentz equivalent decompositions of the $\gamma N \rightarrow \gamma N$ Compton amplitude produce inequivalent self-energies, WLCM use a subtracted dispersion relation to remove the ambiguity. This revision modifies traditional values of the EM part of the baryon mass splittings.

It is clearly valuable to independently determine either the strong or EM contribution to the proton-neutron mass difference. In principle this is achievable with lattice QCD. At this time, however, most lattice simulations for the octet baryon masses are performed with 2+1 quark flavours, that is, with mass-degenerate light quarks: $m_u = m_d$. Our analysis uses isospin-averaged lattice simulation results\textsuperscript{23,24} to constrain chiral perturbation theory expressions for the baryon masses. Because of the symmetries of chiral perturbation theory, the only additional input required to determine the strong contribution to the baryon mass splittings is the up-down quark mass ratio $m_u/m_d$. The remainder of this section is devoted to an illustration of this method.

The usual meson-baryon Lagrangian can be written

$$\mathcal{L}^B = i \text{Tr} \left( v \cdot D \right) B + 2D \text{Tr} \left( \overline{B} S^\mu \left[ A_\mu, B \right] \right) + 2F \text{Tr} \left( \overline{B} S^\mu \left[ A_\mu, B \right] \right) + 2b_D \text{Tr} \left( M_q, B \right) + 2b_F \text{Tr} \left( M_q, B \right) + 2\sigma_0 \text{Tr} \left( M_q, \text{Tr} \overline{B} B \right).$$

The $D$ and $F$ terms denote the meson-baryon interactions and generate the nonanalytic quark mass dependence associated with quantum fluctuations of the pseudo-Goldstone modes. The explicit quark mass dependence is carried by the mass matrix $M_q$, which is related to only three undetermined low-energy constants: $b_D$, $b_F$ and $\sigma_0$ (at this order). With these constants determined by a fit to isospin-averaged (2+1-flavour) lattice data, there are no new parameters in the effective field theory relevant to CSV. Combined with appropriate treatment of the CSV loop corrections, our analysis of two independent lattice simulations yields the charge symmetry-breaking derivative\textsuperscript{19}

$$m_\pi^2 \frac{d}{d\omega} (M_n - M_p) = (20.3 \pm 1.2) \text{ MeV} \quad [\text{PACS-CS}]$$

$$m_\pi^2 \frac{d}{d\omega} (M_n - M_p) = (16.6 \pm 1.2) \text{ MeV} \quad [\text{QCDSF}].$$

Here the quark mass splitting is denoted by $\omega$, which is related to the quark mass ratio ($R = m_u/m_d$) by

$$\omega = \frac{1}{2} \frac{1 - R}{1 + R} m_\pi^2 \text{ (phys)}. \quad (1)$$
The dependence of our determination of \((M_p - M_n)^\text{Strong}\) on the input quark mass ratio is indicated in Fig. 1. In Figure 2 this analysis, where we consider both PACS-CS and Leutwyler results and allow for both Leutwyler and FLAG values of the ratio \(m_u/m_d\), is compared against a recent strong mass splitting calculation of the BMW Collaboration\(^{27}\) and the phenomenological estimates of the electromagnetic self energy.\(^{21,22}\) Only for the purpose of simplifying the graphic have we not shown other recent lattice QCD estimates of the strong contribution to the mass splitting.\(^{28-31}\)

3. CSV parton distribution moments

The spin-independent CSV Mellin moments are defined as

\[
\delta u^{m\pm} = \int_0^1 dx x^m (u^{p\pm}(x) - d^{n\pm}(x)) = \langle x^m \rangle_{u}^{p\pm} - \langle x^m \rangle_{d}^{n\pm},
\]

\[
\delta d^{m\pm} = \int_0^1 dx x^m (d^{p\pm}(x) - u^{n\pm}(x)) = \langle x^m \rangle_{d}^{p\pm} - \langle x^m \rangle_{u}^{n\pm},
\]

with similar expressions for the analogous spin-dependent terms \(\delta \Delta q^{\pm}\).

Here, the plus (minus) superscripts indicate C-even (C-odd) distributions.
The first two spin-dependent and first spin-independent lattice-accessible moments have recently been determined from 2 + 1–flavor lattice QCD by the QCDSF/UKQCD Collaboration.\textsuperscript{12,13} These original papers made first estimates for the amount of CSV in the parton moments by considering the leading flavour expansion about the SU(3) symmetric point.\textsuperscript{12,13} In Ref.\textsuperscript{11} we applied an SU(3) chiral expansion in the same fashion as the baryon mass expansion described above. This enabled us to extrapolate the results away from the SU(3) symmetric point to determine the CSV contribution at the physical quark masses. Although this work only determines the lowest nontrival spin-independent moment, we can infer the CSV distribution as shown in Fig. 3 by using the same parameterisation of the $x$ dependence as Ref.\textsuperscript{4} This magnitude of charge symmetry breaking is found to be in agreement with phenomenological MIT bag model estimates.\textsuperscript{32,33} This result is of particular significance in the context of a new program to measure the (PVDIS) asymmetry to high precision at Jefferson Laboratory.\textsuperscript{5,34}

Further, $q^\pm(x) = q(x) \pm \overline{q}(x)$. 

![Figure 2. Status of the nucleon mass splitting decomposition. Gasser-Leutwyler\textsuperscript{21} and WLCM\textsuperscript{22} calculations of the electromagnetic contribution are compared with the strong contribution determined in this work\textsuperscript{19} and by the BMW lattice collaboration.\textsuperscript{27} The black line indicates the experimental determination of the total mass difference.\textsuperscript{20}](image-url)
the sign and magnitude of these results suggest a 1-\(\sigma\) reduction of the NuTeV anomaly.\textsuperscript{15}

4. Octet baryon spin fractions

In addition to using the chiral extrapolation of the previous section to extract CSV effects, we have also determined the relative quark spin fractions in the octet baryons.\textsuperscript{18} Figure 4, taken from Ref.,\textsuperscript{18} illustrates that the quark spin fraction is environment dependent. The figure clearly highlights that this result is evident in the bare lattice results, with considerable enhancement seen in the extrapolation to the physical point. Clearly, any candidate explanation of the proton spin problem must allow for the fraction of spin carried by the quarks to be dependent on baryon structure.

This finding is supported by a Cloudy Bag Model calculation, which includes relativistic and one-gluon-exchange corrections.\textsuperscript{35–37} Within this model, the observed variation in quark spin arises from the meson cloud correction being considerably smaller in the \(\Xi\) than in the nucleon. That, combined with the less relativistic motion of the heavier strange quark, results in the total spin fraction in the \(\Xi\) being significantly larger than in the nucleon.

5. Conclusion

The effects of charge symmetry violation (CSV) are becoming increasingly significant in precision studies of the Standard Model. Recent results, based
on 2+1–flavor lattice QCD simulations, unambiguously resolve CSV in the quark Mellin moments. These results reduce the NuTeV anomaly from 3σ to 2σ and could improve the sensitivity of Standard Model tests such as the PVDIS program at Jefferson Laboratory. The same lattice QCD studies show that the fraction of baryon spin carried by the quarks is structure-dependent, rather than universal across the baryon octet.

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