Overview of Issues Surrounding Strangeness in the Nucleon

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Abstract. The calculation of the strangeness content of the nucleon and its experimental verification is a fundamental step in establishing non-perturbative QCD as the correct theory describing the structure of hadrons. It holds a role in QCD analogous to the correct calculation of the Lamb shift in QED. We review the latest developments in the vector and scalar matrix elements of the strange quarks in the proton, where there has recently been considerable progress.

Keywords: strange quarks, Lamb shift, lattice QCD, parity violating electron scattering

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INTRODUCTION

Over the past decade there have been heroic efforts at MIT-Bates, Mainz and JLab [1, 2, 3, 4] to use parity violating electron scattering to extract the vector matrix elements of the strange quarks in the proton, \( \langle \bar{s} \gamma^\mu s \rangle \). These measurements have allowed a careful global analysis from which it has been established that less than 5% of the magnetic moment and less than 2% of the charge radius of the proton can be attributed to strange quarks [5, 6]. At this meeting the G0 Collaboration reported preliminary results from its final backward angle run [7], in which new information on the strange magnet form factor and the axial form factor at high \( Q^2 \) were presented. On the theoretical side there was also a presentation from the University of Kentucky group concerning the direct measurement of the strange magnetic form factor [8].

The scalar form factors of the nucleon have been of great theoretical interest for decades, because the \( \pi N \) and strange quark sigma commutators

\[
\sigma_{\pi N} = \frac{(m_u + m_d)}{2} \langle \bar{u}u + \bar{d}d \rangle; \quad \sigma_s = m_s \langle \bar{s}s \rangle,
\]

are directly related to the chiral symmetry breaking in the QCD Hamiltonian. Both have been somewhat controversial in terms of their extraction from experimental data and in fact it seems unlikely that the strange sigma commutator, which has long been believed to account for as much as one third of the mass of the nucleon, will ever be extracted from data with any degree of precision. Currently, these terms are of some practical importance in an unexpected quarter, namely the search for dark matter. Within the constrained, minimal supersymmetric extensions of the Standard Model, the neutralinos are a promising candidate for dark matter and their interaction with hadronic matter is determined by the sigma commutators [9]. This means that the interpretation of the results of dark matter searches depends strongly on how accurately one can determine
σπN and σσs. As we shall explain, the answer to this need has come from an unexpected source, namely the study of hadron properties as a function of quark mass using lattice QCD [10].

VECTOR STRANGE FORM FACTORS

The determination of the contribution to nucleon properties from quark loops, the so-called “disconnected terms” in lattice QCD, has proven very difficult by direct means. This led to the formulation of indirect methods [11], which have proven extremely effective in extracting accurate values for the strange contributions to the electric and magnetic form factors [12, 13]. For example, for the strangeness magnetic moment was determined by these means to be \(-0.046 \pm 0.019 \mu_N\) [12], which at just a few hundredths of a nuclear magneton represents a remarkably accurate determination.

Recently, there has been significant progress in the development of direct methods for calculating the contribution from quark loops. First, for the measurement of the moments of parton distribution functions, the University of Kentucky group employed sophisticated numerical methods to extract a non-zero signal for the momentum fraction carried by strange and anti-strange quarks in the proton [14], namely \(\langle x(s + \bar{s}) \rangle = 0.027 \pm 0.006\) – albeit at a somewhat large light quark mass. This was recently followed [15], as reported at this meeting by Keh-Fei Liu [8], by a clear non-zero signal at a range of momentum transfer values for the strangeness magnetic form factor. At the large light quark masses employed, the value obtained at zero momentum transfer was \(G_M(Q^2 = 0) = -0.017 \pm 0.025 \pm 0.07 \mu_N\). Using the dependence on light quark mass found in Ref. [16], this would be expected to increase in magnitude by about 80% at the physical light quark mass. With or without the latter correction, this direct determination is clearly in excellent quantitative agreement with the earlier calculation of Leinweber et al. [12].

The best experimental determination of the strange magnetic form factor, at \(Q^2 = 0.1\) GeV\(^2\), from a global analysis of all published data [6], is \(-0.01 \pm 0.25 \mu_N\). Clearly this is in very good agreement with the theoretical values. However, in a unique example for strong interaction physics, the theoretical calculations are an order of magnitude more precise than the state of the art experiments! This makes the quest for really bright new ideas to improve the experimental accuracy very important indeed.

With the theoretical and experimental values of the strange form factors pinned down near \(Q^2 = 0\), it is interesting to also explore the dependence on \(Q^2\). At higher \(Q^2 = 0.22\) GeV\(^2\), the A4 Collaboration at Mainz recently reported a new value of the strange magnetic form factor [17], namely \(-0.14 \pm 0.11 \pm 0.11 \mu_N\), again in very good agreement with the latest application of the indirect methods [18] \(G_M(Q^2 = 0.22) = -0.034 \pm 0.031 \mu_N\). The G0 Collaboration reported a preliminary analysis of its back angle run at this conference, with the value at 0.23 GeV\(^2\) consistent with the Mainz measurement [7]. It also seems likely that the collaboration will determine the axial form factor at the larger \(Q^2\) values.
Scalar Form Factor

The strange sigma commutator, $\sigma_s$, is tricky to measure directly in lattice QCD because it involves a subtraction of the strange quark loop in vacuum from that in the nucleon and as we shall see the difference is relatively small. While the common belief is that it is of order 1/3 of the mass of the nucleon [19], the first hint that it may be much smaller came in a study made in connection with the possible experimental determination of a time dependent variation in the fundamental “constants” of Nature [20]. However, it is only this year, with the analysis of a several independent, high precision data sets on the masses of the nucleon octet, within full 2+1 flavor QCD [21, 22], that it has been possible to make a precise mass formula which incorporates the correct non-analytic behavior and reproduces all of the data in a convincing manner [10]. The mass formula involves the usual SU(3) expansion to first order in the quark masses, plus the one loop chiral corrections including the Goldstone boson masses and evaluated using finite range regularization.

This procedure not only produces an excellent fit to all of the data but the octet masses extrapolated to the physical point all agree with experiment at the 2% level or better. Given the expressions for the masses versus $m_\pi$ and $m_K$ one can directly evaluate the sigma terms using the Feynman-Hellman theorem. The result for $\sigma_{\pi N} = 47 \pm 10$ MeV is certainly consistent with most studies. However, the result for the strange term, $\sigma_s = 31 \pm 16$ MeV is an order of magnitude smaller than the classic result. It is this order of magnitude reduction that is expected to have profound implications for searches for dark matter [23].

After the determination by Young and Thomas [10], a new direct calculation of $\sigma_s$ was reported by Touassaint and Freeman [24]. Their value of $59 \pm 11$ MeV is consistent with that reported above and appears to confirm that $\sigma_s$ is considerably smaller than hitherto believed.

CONCLUSION

The last few years have seen remarkable progress in both the theoretical and experimental determination of the strange quark matrix elements in the proton. For the present time the theoretical calculations hold the precision lead with a great need for new ideas if the experimental determinations are to reach a similar level. Nevertheless, within the currently possible limits, QCD works very well and by analogy with the Lamb shift in QED, non-perturbative QCD has satisfied a crucial test.

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