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A vision of hadronic physics

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Abstract. We present a vision for the next decade of hadron physics in which the central question being addressed is how one might win new physical insight into the way hadronic systems work. The topics addressed include the relevance of model building, the role of spontaneously broken chiral symmetry, spectroscopy, form factors and physics in the deep inelastic regime.

1. Introduction

At times physics can be a very hard way to make a living. There can be few professions where one can work hard all day and go home feeling more stupid than when the day began. And yet, there are times when it is all worthwhile, when it really was worth the effort of getting out of bed. What makes it worthwhile, instills in us a sense of real achievement, is the feeling that one has actually won some new insight into how Nature works. My vision for the next decade is that, as a community, we will develop a clearer and more satisfying picture of the structure of hadrons and nuclei within the framework of QCD. This quest will, of course, involve new data and calculations of ever higher precision but, more than that, it will involve new physical insight and understanding.

2. Models

There are some who are less than thrilled by the use of models in hadron physics and yet they are of fundamental importance. Flawed as all models necessarily must be, they are a vital part of the machinery needed to imagine new ideas and new ways of investigating Nature. Rather than arguing in generalities I briefly recall some examples of insights arising from models that have proven critical in motivating new experiments and guiding the development of our current understanding of hadron structure.

2.1 Flavor asymmetries

Although Sullivan and Feynman [1] had suggested in the early 70's that the pion cloud of the nucleon might be significant in deep inelastic scattering (DIS), it would be fair to say that this was not taken at all seriously a decade later. Then, motivated by the cloudy bag model (CBM) [2, 3], their approach was used to explain the known asymmetry between strange and non-strange sea quarks in the nucleon [4], most particle physicists ignored the work. Everyone knew that partons were non-interacting on the light-cone and this was generally taken to mean that clusters, such as a highly correlated $q-\bar{q}$ pair in a virtual pion, could not be relevant to deep inelastic scattering (DIS). Yet that same calculation also showed that the dominance of the $\pi^+ - n$ component in the chiral structure of the proton implied an excess of $\bar{d}$ over $\bar{u}$ quarks in the proton sea. Again this was ignored.

A decade later it was discovered that there was a very large violation of the Gottfried sum rule [5] and later Drell-Yan experiments [6, 7], followed by semi-inclusive DIS measurements [8], confirmed that this originated in an excess of $\bar{d}$ over $\bar{u}$ quarks consistent with the 1983 prediction [9–11]. The pion cloud of the nucleon, which had led to the prediction of precisely such an effect slowly began to be taken more seriously and new experiments are still being planned to explore the phenomenon in detail [12].

Investigations of the structure functions of the nucleon within models such as the MIT bag [13] and the chiral quark soliton model [14] predicted non-trivial polarization of the anti-quarks in the proton sea arising from the modification of the vacuum inside a hadron, with $\Delta\bar{u} > 0$ and $\Delta\bar{d} < 0$. Experiments underway at RHIC have the capacity to tell us whether indeed this is the way Nature works.

There is an almost universal assumption of charge symmetry [15, 16] (e.g. $u \equiv u^p = d^n$) in the literature concerned with parton distribution functions. Indeed, phenomenological fits allowing for the possibility of charge symmetry violation (CSV) were only initiated a decade ago [17]. Yet bag model investigations some 20 years ago had unambiguously predicted the sign and magnitude of CSV in the valence quark distributions [18, 19]. The neglect of those predictions which, at least for low moments, have been confirmed by lattice QCD calculations [20] in just the last few years led to an over-inflated view of the importance of the deviation from the Standard Model expectations in neutrino-nucleus DIS.

Later studies of the NuTeV anomaly have also revealed, again within a QCD motivated model of the EMC effect, the possibility of an additional source of difference between u and d valence quarks in nuclei with $N \neq Z$. This difference, called the iso-vector EMC effect [21], is a consequence of the iso-vector nuclear force acting on the bound quarks. Again, this insight from a model has suggested a number of experiments, including parity violating DIS on nuclei [22], which have the capacity to establish the phenomenon.

2.2 Spin

The proton "spin crisis" resulting from the EMC measurements [23, 24] of a large violation of the Ellis-Jaffe sum rule have inspired theorists to find ways to explain it. Within a few months of the experimental paper two very different approaches were proposed. The theoretical beauty of the axial anomaly in QCD led to a rush to explore the possibility that at a scale of a few GeV^2 gluons might carry as much as 4 units of angular momentum, which through the box diagram containing the axial anomaly would resolve the crisis [25]. No-one ever suggested how such an enormous gluon spin fraction might arise and eventually a new generation of polarized pp collider measurements have shown that indeed it does not exist [26].

The alternative suggestions based on rather well understood hadronic physics, which were initially left in the dust now appear to be correct. In particular, when a pion is emitted the proton tends to flip its spin, $p\uparrow \rightarrow \pi^+ + n\downarrow$, and within the CBM it was shown that this naturally accounts for half of the modern discrepancy [27]. In addition, within essentially all QCD inspired quark models, the exchange of a single gluon is an essential part of the machinery needed to explain the hadron spectrum. For example, within the MIT bag model the $N-\Delta$ and the $\Sigma-\Lambda$ splitting both arise from the one-gluon-exchange hyperfine interaction [28]. This same interaction *required by spectroscopy* naturally reduces the fraction of spin carried by the quarks [29]. Combining these two effects fully accounts for the current experimental value [30] and lattice results [31].

Of course, the "experimental value" is not independent of theory, because one must subtract the octet component of the nucleon spin (g_A^8) from the experimental data to obtain the singlet spin fraction. Again, recent studies within the CBM suggest that SU(3) symmetry is broken by as much as 20% in this case [32] and that has a significant effect on the deduced value of the proton spin fraction. Incidentally, since many fits to spin dependent PDFs impose an assumed value of g_A^8, this also has implications for the phenomenological spin dependent PDFs.

2.3 Lattice QCD

As lattice QCD has developed into a reliable, quantitative tool for calculating hadron properties within QCD one might imagine that models would be irrelevant. Yet that is far from correct. In the quest to understand how QCD works, lattice studies have created a new dimension to that occuring in Nature, namely the study of hadron properties as a function of quark mass. Initially, even for ground state masses, it was essential to work with unphysical quark masses and to extrapolate to the physical quark masses in some way. This is still true now for many form factors and excited state properties. The CBM provided vital guidance in early studies of this kind [33] and eventually inspired what has become known as finite range regularization (FRR) [34, 35]. This approach has provided a natural explanation of the general absence of chiral curvature at quark masses above 40–50 MeV in *all hadronic observables*. It led to the precise calculation of the electric and magnetic strange form factors of the nucleon [36, 37] and provided a “back of the envelope” understanding [38] of why those are so remarkably small.

3. Spectroscopy

As we hinted above, the situation with respect to excited states calculated using lattice QCD is far more fluid. The JLab and CSSM groups have made enormous progress at light quark masses two or three times the physical value, with as many as 4 or more excited states found for a given set of quantum numbers [39, 40]. It is still far too early to draw conclusions concerning the pattern of these excitations with respect to experiment. Nevertheless, this area will move rapidly over the next few years. As an indication of just what may be possible in terms of insight we mention the study of the wavefunction of the Roper resonance by Leinweber and collaborators [41], which clearly shows the node indicative of a $2s$ excitation. Since the Roper, along with the $\Lambda(1405)$, has been a bugbear in spectroscopy for decades (e.g. as to whether it is a multi-quark state, involves gluonic excitation, etc.), direct pictures of the distribution of quarks within the state should prove extremely valuable in solving the mystery.

The second major issue in hadron spectroscopy that must be mentioned is the existence, or otherwise, of exotic hadrons. The JLab lattice studies strongly suggest that these exist at an excitation energy perhaps 0.8 to 1.0 GeV above the corresponding non-exotic hadrons [42]. This is consistent with the cost in terms of energy found in the MIT bag or much more recently within the Dyson-Schwinger formalism [43]. Clearly the major advances in this area must initially be tied to the success of the experimental searches, for example at JLab 12 GeV.

4. Form factors

No discussion of this topic at the present time would be complete without a mention of the mystery surrounding the charge radius of the proton following the muonic-hydrogen measurement of Pohl and collaborators [44]. At the present time the discrepancy between that beautiful measurement and the CODATA value is not understood at all and there is a distinct possibility that further investigation may reveal a hint of new physics, perhaps related to the muonic $g-2$ discrepancy. In this case there is no model we can point to for inspration.

At higher Q^2 the JLab discovery of an anticipated decrease in the ratio of the electric to magnetic form factors of the proton is of great interest [45]. We look forward to seeing data at even higher Q^2 to show for certain whether or not G_E passes through zero. Lattice QCD has not yet reached these exulted values of momentum transfer but there has been some notable progress below 1.5 GeV^2 [46]. In terms of a deeper understanding of the physics in the region 5–10 GeV^2, the recent link between the behaviour of G_E/G_M and the transition between non-perturbative and perturbative behaviour in the quark propagator suggested in a recent Dyson-Schwinger equation calculation makes it very interesting indeed [47].

We already mentioned the success in both measuring and calculating the strange electric and magnetic form factors of the proton, which have occupied many people for the last two decades. This is a vital test of our understanding of non-perturbative QCD, in close analogy with the standing of the Lamb shift in QED. This because these form factors have their origins in so-called "disconnected diagrams", or non-valence physics, just like vacuum polarization. Pushing these tests to higher precision is at a stand still for the time being as one looks for new experimental techniques and tries to pin down the extent of CSV in the nucleon elastic form factors.

5. The Deep inelastic regime

Over the past 40 or more years unpolarized DIS measurements have managed to define very precisely many important properties of the PDFs of the nucleons. There are cases where physics demands at the LHC may need more but, at least for unpolarized scattering, it is in the area of flavor asymmetries that the most interesting questions remain open. We have already mentioned most of these issues in Sect. 2. Semi-inclusive DIS is one promising technique to explore such questions but, especially once it comes to strange quarks and fragmentations functions that involve koans or unfavoured fragmentation there is much we do not know. Model studies may well provide useful information there [48].

However, it is in the measurement of processes involving polarization that there is the greatest activity. The next decade will see a revolution in our understanding of the Collins and Sivers effects, of deeply virtual Compton scattering and so on. Perhaps because we are at such an early stage in this work, there is a great deal of effort needed to build better models that more accurately reflect the consequences of QCD itself. Eventually we may hope for a much deeper understanding of the role of orbital angular momentum in hadrons. We already know that the conversion of valence quark spin into quark orbital angular momentum, carried by pions and anti-quarks, is the explanation for the EMC spin crisis, but the finer details demand much more effort.

6. Conclusion

In this very limited space it has been impossible to do more than set out a rough sketch of a vision for hadronic physics over the next decade. New facilities such as JLab at 12 GeV, GSI-FAIR, J-PARC and one or more electron-ion colliders, backed by upgrades at RHIC, will provide essential new data. Lattice QCD will continue to grow in reliability and accuracy. We will probe the QCD structure and origins of atomic nuclei in new ways. Yet, in the end, our success will be judged by the new insights into how hadrons work, the new paradigms that are established. It will be the leaps in our qualitative understanding, many related to the beauty of new models that capture the essence of the hadronic systems that will stand out. These are exciting times.

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