Glimpsing Colour in a World of Black and White

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Abstract. The past 40 years have taught us that nucleons are built of constituents that carry colour charges with interactions governed by Quantum Chromodynamics (QCD). How experiments (past, present and future) at Jefferson Lab probe colourless nuclei to map out these internal colour degrees of freedom is presented. When combined with theoretical calculations, these will paint a picture of how the confinement of quarks and gluons, and the structure of the QCD vacuum, determine the properties of all (light) strongly interacting states.

A hundred years ago, Rutherford demonstrated that the experimental results of his colleagues, Geiger and Marsden, pointed to there being a tiny nucleus at the heart of every atom. This started off the field we celebrate at this meeting. For awhile it was believed that each nucleus was a collection of protons and neutrons held together by some strong nuclear force. However, over the past 50 years, we have learnt that inside nuclei not only are protons and neutrons present, but also dozens, even hundreds of other short lived particles, we call collectively hadrons. Hadrons fall into two classes: baryons, of which the proton is the only stable example, are fermions, and mesons, of which the pion is by far the lightest, are bosons. These could be understood if each were themselves built of constituents, quarks: each meson made of a quark and an antiquark, and every baryon with three quarks. In 1970 we knew of just three flavours of quark, up, down and strange, but in quick succession heavier quarks, charm and bottom, and then top were discovered. For this paper we restrict discussion to the world of just the lightest three flavours of quark, \( u \), \( d \) and \( s \) of which we are made. This places the proton and neutron in an octet of ground state baryons, and the three differently charged pions in a nonet of ground state pseudoscalar mesons. Deeper probing, in the spirit of Rutherford, has taught us that there really are quarks inside hadrons, but however hard we hit them they never leave the femto-universe alone. Quarks can then not just be “bits” of a proton or a neutron, but rather must have a property that nucleons don’t have: a property we call colour. While hadrons are colour neutral, quarks carry colour bound by a force governed by Quantum Chromodynamics (QCD).

This paper is a brief review of the work of Jefferson Laboratory (JLab) that sets out to understand these colour degrees of freedom. JLab studies protons and neutrons in fine detail, alone and within nuclei, using an electron beam as a probe. This includes important parity violation experiments that measure the interference between the photon and the \( Z \)-boson to study the weak charges of quarks and leptons. These experiments are covered in the paper by Michael Ramsey-Musolf [2]. Other parity violation experiments, like PREX, use the weak interaction too to measure the neutron skin of nuclei, like lead [1]. Understanding this is important for the workings of astrophysical objects, like neutron stars. Here I will concentrate on hadron physics and the strong interaction at JLab.
Figure 1. Deep inelastic electron scattering on a proton is shown on the left. As the photon virtuality, $Q^2$, increases (depicted on the right), the photon wavelength shortens and it probes the proton’s internal structure at shorter scales. The cross-section can be expressed in terms of $x f(x)$ the momentum distribution of the constituents of the proton. Bjorken $x$ is the fraction of its longitudinal momentum carried by the struck “parton” in the light cone or Breit frame. At low $Q$ (or long wavelength) the photon sees the whole proton. As $Q$ increases, it begins to see the valence quarks, and then as the wavelength shortens further, the current quarks, sea of $\bar{q}q$ pairs and cloud of gluons. Above a $Q$ of $\sim 3$ GeV, the evolution of the momentum distribution $x f(x)$ sketched here is governed by perturbative QCD.

As the CEBAF accelerated electron approaches a nuclear target, it feels the proton charge and emits a virtual photon that probes inside the proton, Fig. 1. In a frame in which the nucleon moves at relativistic speeds, the photon sees the proton’s longitudinal momentum shared by its valence quarks and a cloud of gluons. At higher energies, the photon having still shorter wavelength sees an increasingly important sea of quark and antiquark pairs each carrying a smaller and smaller fraction of the proton’s momentum. This evolution is governed by perturbative QCD and is well understood. What JLab studies is what happens when we just open the nucleon box and peer inside, Fig. 1. JLab experiments also investigate how these momentum distributions change when the nucleon is inside a nucleus. Then in principle the quarks no longer know which nucleon they belong to and move from one to the other. Indeed, at tiny values of $x$ this may then lead to new states of matter to be explored at a possible future Electron-Ion Collider.

Of course, the components of the proton not only carry its longitudinal momentum, its flavour and spin, but are distributed in transverse space, Fig. 2. A new era of tomography of the proton has started [3]. HERMES, COMPASS and JLab@6 GeV [4] have shown that generalized parton distributions (GPDs) and transverse momentum distributions can be studied in semi-inclusive deep inelastic processes and deeply virtual Compton scattering. The extraction of these will require close cooperation between experimentalists and theorists: a feature of JLab physics particularly in the upcoming era of precision data. A major effort is on the way to predict what QCD can tell us about this internal landscape, Fig. 2, as well as interpret data in terms of QCD.

This joint engagement of theory and experiment is also a key part of the program in hadron spectroscopy, to which we now turn. With quark spins combined with units of orbital angular momentum we expect whole towers of hadrons beyond the ground states. For many, seeking these states is mere stamp-collecting. Indeed it was Rutherford who said “all of science is either physics or stamp-collecting”. What I want to convince you of is that spectroscopy is physics. The paradigm is the spectrum of photons emitted by excited atoms. Even if we did not have enough energy to separate a nucleus from its surrounding electron cloud, the spectrum alone would
teach us that atoms, though electrically neutral, behaved as if they were made of electrically charged objects held together by an electromagnetic force, governed by the rules of quantum electrodynamics. In an analogous way, colour neutral hadrons can teach us about the rules that lead to the confinement of quarks and thereby all the properties of light hadrons. We believe we know the underlying theory, namely quantum chromodynamics (QCD). At short distances, the up and down quarks are almost massless and interact only weakly with the octet of coloured gluons. Hard probing confirms QCD is correct to high precision in the short distance regime ($\ll 1\text{ fm}$). However, the properties of hadrons made of light quarks and glue are controlled by interactions at the distance of $\sim 1\text{ fm}$, where the strong interaction is strong and the vacuum filled with condensates. There accurate wholly theoretical calculations are much more difficult. Consequently, experiment provides critical guidance, which when combined with theory, is the key to understanding the colour degrees of freedom.

While the colour neutral wavefunction of a meson is a sum of quark-antiquark terms regardless of the number of colours, that for a proton at its simplest involves $N_c$ valence quarks in $N_c$ colours, carrying electric charges in units of $1/N_c$. Baryons directly reflect the non-Abelian nature of QCD. But are hadrons just a collection of a minimal number of valence quarks? Is the sole role of gluons to create the QCD vacuum that dresses almost massless $u$ and $d$ current quarks into constituent quarks of 300 MeV? Or can gluons form massive constituents themselves?

The motivation for the quark model in the first place was that it reproduced the low mass baryons found in experiment [5]. The same model with three pointlike quark degrees of freedom [6] has long predicted the spectrum of excited nucleons and $\Delta$’s. However, experimentally the excited spectrum above 1.6 GeV (or so) is far from clear. At first it was thought this was because the main source of information came from $\pi N$ elastic scattering, and perhaps the higher mass states coupled pre-dominantly to $\pi\pi N$ and $KY$ channels. More recent exploration of these final states in both hadro and electroproduction has revealed little more certainty from the gloom [7]. This is in part because multi-channel analyses are difficult, lengthy and time-consuming. Nevertheless such analyses point to large numbers of expected excited baryons being absent. This could readily be explained [8], if the degrees of freedom in

**Figure 2.** With the hadron moving in the $z$-direction, the figure [3] illustrates how different physical quantities map both the longitudinal momentum (i.e. $x$) distribution and the transverse spatial distribution of the “partons” inside the hadron. Elastic form-factors involve just the transverse distribution, the structure functions of Fig. 1, the longitudinal momentum distribution, while generalized parton distributions (GPDs) depend on both variables.
a baryon are restricted to a quark and a point diquark (with two of the valence quarks always pairing up). However appealing, is this modelling really QCD?

Moreover, in the simple quark model the spectrum computed is of stable states. The coupling to $\pi N$, $K Y$ and even $\rho N$ are popularly computed in a $3P_0$ model of $\bar{q}q$ creation [9]. This allows an estimate of widths to decay channels, but how these feed back on the “bare” masses is generally disregarded. Of course, heavier states are broader, spend less time in their simplest Fock state but rather linger in multi-hadron modes, like $\pi\pi N$. These effects are not minor perturbations.

Strong coupling QCD has long been studied on the lattice. Nevertheless, it is only now [10] that the baryon spectrum has been computed in fine detail with sufficient precision to reveal that the calculated states are naturally grouped in the $SU(6) \times O(3)$ structures of the 3-valence quark model, Fig. 3, with no support for pointlike diquark components. The experimentally missing states should be there. While hadronic channels are implicit among the operators used in these lattice calculations, the pion mass is 5 (and at best 3) times its physical value. Consequently decay channels have limited effect. This is an issue the lattice must urgently address if it is to relate to the experimental light hadron sector.

Experience from heavy flavour factories has revealed an unexpected richness of the charmonium spectrum above $D\bar{D}$ threshold. While below, the spectrum is essentially that of a non-relativisitc potential, above open charm thresholds, decay channels not just distort the spectrum but add new states that are generated by inter-hadron forces. Some of these are remarkably narrow. Such dynamics is highly specific to the proximity of nearly open and nearby virtual hadron channels. In other configurations, calculations show that states in the spectrum without decays can just as likely merge into the continuum, when open channels are included.

Similarly for baryons, coupled channels are essential to all states above the nucleon. Such hadron modes are an integral part of the mammoth EBAC effort [11]. There within a specific Lagrangian framework a comprehensive list of meson, photon and electron induced baryon production channels are fitted, differential cross-sections and polarisation asymmetries, for instance those in Fig. 4 on $\gamma N \rightarrow \pi N$ [12], starting from the results of the $\pi N$ phase shift analysis of the SAID group [13]. On the basis of such fits to some $10^5$ datapoints, one can determine the mass, width and couplings of excited baryon resonances. The resulting lowest

![Figure 3. Lattice calculation in full QCD of the baryon spectrum at a pion mass of 520 MeV from [10] labelled by $J^P$ in units of the $\Omega$ mass, showing the groupings into $SU(6) \times O(3)$ multiplets.](image)
Figure 4. The upper 5 graphs are for $\gamma p \rightarrow \pi^0 p$ and the lower 5 for $\gamma p \rightarrow \pi^+ n$. On the left are the integrated cross-sections as functions of c.m. energy, $W$. On the right are differential cross-section and polarisation asymmetry, $\Sigma$, as functions of the c.m. scattering angle $\theta$, from [12].

$I = 1/2 \pi N$ waves [14] are illustrated in Fig. 5, as an example. Moreover, within such a modelling as that of EBAC [15], hadron channels can be tuned in and out. A striking effect is in the $P_{11}$ channel, where the physical states, the $N^*(1440)$ (the Roper), and the $N^*(1710)$ reside as poles in the complex energy plane. When $\eta N$ and $\pi\Delta$ decay channels are switched off, these two poles move to the real axis merging as a single entity at $\sim 1800$ MeV. Perhaps it is this single “bare” state that should be compared to the simple quark model, or even dynamical calculations in the Schwinger-Dyson/Bethe-Salpeter Equation approach [16], and not two $N^*$'s.

However, the rules of the dynamics, viz QCD, that bind these quarks into hadrons lead us to expect an even richer spectrum, in which multiple $\bar{q}q$ pairs as well as gluons contribute to the

Figure 5. The imaginary parts of the lowest $\pi N$ partial waves are shown as a function of centre of mass energy, $W$ from the EBAC analysis of Julia-Diaz et al. [14]. The waves are labelled by the orbital angular momentum $L$ of the $\pi N$ system, its isospin $I$ and total spin $J$ as $L_{2I2J}$. As an illustration only those with $I = 1/2$ are shown.
Figure 6. Sketch of a typical quark-antiquark meson on the left, where the gluon flux just holds the constituent quarks together, while on the right is a hybrid meson, in which the gluon flux contributes in an essential way to the angular momentum of the hadron.

quantum numbers of hadrons. As already alluded to, the charmonium sector gives strong hints of multiquark or molecular states, to which the strangeonium sector of the \( f_0/a_0(980) \) can be added. However, finding states in which glue is an essential component, not just in generating binding as it does for all hadrons, but contributing as a basic degree of freedom would reveal much about the longer range dynamics present inside all hadrons. It is in the meson sector that it is a little easier to predict how this might be present.

The quark model of mesons gives simple rules determining the allowed spin \( J \), parity \( P \) and charge conjugation \( C \), denoted collectively as \( J^{PC} \). Finding mesons outside of the permitted values has been a thrust of meson spectroscopy for several decades. A discovery of states with \( J^{PC} \) like \( 1^{-+} \) or \( 0^{+-} \) would point to glue, or additional \( \bar{q}q \) pairs, being essential to their make-up, Fig. 6. On the lattice, colleagues at JLab [17] have in full (i.e. unquenched) QCD computed the spectrum with \( \bar{q}gq \) operators with unprecedented precision. These predict \( 1^{-+} \) states below 2 GeV, with \( 0^{+-} \) and \( 2^{+-} \) heavier in steps of several hundred MeV — Fig. 7.

Experimental hints of a \( 1^{-+} \) enhancement started with GAMS results [18] on \( \pi^- p \rightarrow \pi^0 \eta n \) at high energy and small momentum transfers. What was novel was that both the \( \pi^0 \) and \( \eta \) were identified by their two photon decays. The \( \pi\eta \) spectrum showed not only the well known \( a_2(1230) \) and \( a_0(980) \), but also revealed a forward backward asymmetry in the 1.4 GeV region.

Figure 7. Lattice QCD calculations of hybrid mesons with quantum numbers \( J^{PC} = 1^{-+}, 0^{+-} \) and \( 2^{+-} \) as a function of quark mass, expressed in terms of the square of the pion mass, \( m_\pi^2 \). The lattice data have to be extrapolated to the physical point, which is essentially where the values of \( J^{PC} \) are drawn. Older lattice results are in black. The newer ones of higher precision are in full QCD from Dudek \textit{et al.} [17].
that hinted at a $P$-wave effect with $1^{-+}$ quantum numbers, but this was never shown to be resonant. The VES experiment studied $\pi^- N \rightarrow \eta\pi^- N$ and $\eta'\pi^- N$ at 37 GeV/c [19]. They similarly found an enhancement in the $\eta\pi$ amplitude around 1400 MeV (Fig. 8 left), with some small phase change relative to the $2^{++}$ wave, and a broad enhancement $\sim 1600$ MeV in $\eta'\pi$.

A higher statistics BNL experiment studied both the $3\pi$ and $\eta'\pi$ final states. These showed what might be a resonant peak around 1.4 GeV at an intensity of a few percent [20], Fig. 9 right. To be certain it is there, one must understand other waves to better than this accuracy. Indeed, subsequent analysis showed that leakage from other partial waves could entirely produce this effect [21] (Fig. 9). However, this was not the case for a higher mass peak and a $\pi_1(1600)$ was claimed [7]. Nevertheless, its signal in the $3\pi$ channel could readily change by a factor of 4 depending on how the various dipion final state interactions were treated [22]. More recently, COMPASS have seen a broad $1^{-+}$ signal in $3\pi$ [23], Fig. 8 right. However, a clean and clear phase variation has not been observed. The analysis of multi-particle final states is complicated with often 20-30 partial waves components required even within a simple isobar picture, Fig. 9.

The 12 GeV upgrade at JLab will not only sharpen our view of the internal landscape of the nucleon, but also dramatically improve the image of the hadron spectrum. In particular, a new experimental hall D will house the GlueX detector specifically designed to investigate the

Figure 8. As functions of di-meson mass are shown with $J^{PC} = 1^{-+}$: the modulus squared of the amplitude, $T$, for the production of $\eta\pi$ and $\eta'\pi$ extracted from data on $\pi^- Be$ interactions at 37 GeV from VES [19] on the left and for the $\rho\pi$ isobar (Fig. 9 left) decaying to $3\pi$ from the COMPASS $\pi^- P$ experiment [23] at 190 GeV (on the right) — fitted to a Breit-Wigner form.

Figure 9. Regge exchange picture of three pion production in $\pi^- p$ interactions at small momentum transfers (on the left) assuming an isobar $R$ is first formed. On the right is the extracted $R = \rho\pi$ signal with $J^{PC} = 1^{-+}$ from BNL-E852 data [22]. The grey histogram is the calculated “leakage” into this channel from other partial waves. The enhancement at $\sim 1.4$ GeV is thereby explained [21], but leaves a clean $\sim 1.6$ GeV enhancement, that might be resonant.
photoproduction of multi-hadron final states into which exotic mesons and baryons may decay, specifically those that may reveal the role that gluons play. This mission is also shared in part by the upgraded hall B detector CLAS12. While experiments will not start till 2014 or even ’15, plans are afoot to bring together a worldwide team of theorists to work with these groups to set the framework for the complex analyses of final state interactions that is required with precision data to unambiguously reveal structures in partial waves, in both moduli and phases, that can point to gluonic degrees of freedom. Such a framework is essential to make the most of the statistics already available with BaBar and Belle data, daily produced in BESIII and LHCb, and yet to come with PANDA@FAIR and JLab@12 GeV.

With signals that are probably only there at a few percent, one needs analyses of even better accuracy. For the most part, present techniques are suited to data an order of magnitude poorer. There is little point taking data of the planned precision without analysis techniques to match. In this way one hopes to be certain to discover hybrid mesons, if they exist, not just with one set of quantum numbers, but in whole flavour multiplets. Similarly, light will hopefully be shed on the “dark” baryon sector. This will usher in an era of certainty in hadron spectroscopy from 1.5 to 2.5 GeV, that with parallel theoretical effort will teach us how QCD, through the confinement of colour and the structure of the vacuum, determines the properties of all the hadrons in the nuclear world. Rutherford started this field in black and white. Little could he have known that we would be colouring in the picture a hundred years later.

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