CLAS & Continuum QCD

Craig Roberts, Physics Division
### Collaborators: 2013-Present

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Classical QCD ... non-Abelian local gauge theory
Remove the mass ... there’s no scale left
No dynamics in a scale-invariant theory; only kinematics ... the theory looks the same at all length-scales ... there can be no clumps of anything ... hence bound-states are impossible.
Our Universe can’t exist
Higgs boson doesn’t solve this problem ... normal matter is constituted from light-quarks ... the mass of protons and neutrons, the kernels of all visible matter, are 100-times larger than anything the Higgs can produce
Where did it all begin?
... becomes ... Where did it all come from?
What is origin of mass in our Universe?

What is the nature of confinement in real (dynamical-quarks) QCD?

How are they connected?

How can any
  – answers,
  – conjectures
  – and/or conclusions
be empirically verified?

*Physics is an Empirical Science*
What is Confinement?
Light quarks & Confinement

Folklore ... *Hall-D Conceptual Design Report* (5)

“The color field lines between a quark and an anti-quark form flux tubes. A unit area placed midway between the quarks and perpendicular to the line connecting them intercepts a constant number of field lines, independent of the distance between the quarks. This leads to a constant force between the quarks – and a large force at that, equal to about 16 metric tons.”
Problem:

16 tonnes of force makes a lot of pions.
Problem:
16 tonnes of force makes a lot of pions.
In the presence of light quarks, pair creation seems to occur non-localized and instantaneously.

No flux tube in a theory with light-quarks.

Flux-tube is not the correct paradigm for confinement in hadron physics.
In the presence of light quarks, pair creation seems to occur non-localized and instantaneously.

- No flux tube in a theory with light quarks.

- Flux-tube is not the correct paradigm for confinement in hadron physics.

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Confinement contains condensates
Brodsky, Roberts, Shrock, Tandy

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Confinement is dynamical
All continuum and lattice predictions for Landau-gauge gluon & quark propagators exhibit an inflection point in $k^2$

⇒ Violate reflection positivity = sufficient for confinement

⇒ Such states have negative norm

⇒ Negative norm states are not observable

⇒ All observable states of a physical Hamiltonian have positive norm

Inflexion point corresponds to $\sigma \approx 0.5$ fm:
Parton-like behaviour at shorter distances; but propagation characteristics changed dramatically at larger distances. $m_g \approx 0.5$ GeV
A quark begins to propagate.

But after each “step” of length $\sigma$, on average, an interaction occurs, so that the quark loses its identity, sharing it with other partons.

Finally, a cloud of partons is produced, which coalesces into colour-singlet final states.

Confinement is a dynamical phenomenon!

Test: compute fragmentation functions & TMDs ⇒ compare with data
\[ S(p) = \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)} \]

DCSB Paradigm
- Dynamical chiral symmetry breaking (DCSB) is a crucial emergent phenomenon in QCD
- Expressed in hadron wave functions not in vacuum condensates
- Contemporary theory indicates that it is responsible for more than 98% of the visible mass in the Universe; namely, given that classical massless-QCD is a conformally invariant theory, then DCSB is the origin of mass from nothing.

- *Dynamical*, not spontaneous
  - Add nothing to $QCD$,
    *No Higgs field, nothing!*
  - Effect achieved purely through quark+gluon dynamics.
Continuum-QCD & \textit{ab initio} predictions
Bridging a gap between continuum-QCD & ab initio predictions of hadron observables

Top down & Bottom up

Top-down approach – ab initio computation of the interaction via direct analysis of the gauge-sector gap equations

Bottom-up scheme – infer interaction by fitting data within a well-defined truncation of the matter sector DSEs that are relevant to bound-state properties.

Serendipitous collaboration, conceived at one-week ECT* Workshop on DSEs in Mathematics and Physics, has united these two approaches

Interaction predicted by modern analyses of QCD’s gauge sector coincides with that required to describe ground-state observables using the sophisticated matter-sector ANL-PKU DSE truncation

Modern kernels and interaction, developed at ANL and Peking U.

One parameter, fitted to ground-state properties without reference to gauge-sector studies.

Modern top-down and bottom-up results agree within 3%!
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**Significant steps toward parameter-free prediction of hadron properties**

Modern kernels and interaction, developed at ANL and Peking U.
One parameter, fitted to ground-state properties without reference to gauge-sector studies.
Modern top-down and bottom-up results agree within 3%!
Enigma of Mass
Pion’s Goldberger-Treiman relation

- Pion’s Bethe-Salpeter amplitude

\[
\Gamma_{\pi^j}(k; P) = \tau^{\pi^j} \gamma_5 \left[ iE_\pi(k; P) + \gamma \cdot PF_\pi(k; P) + \gamma \cdot k \cdot P G_\pi(k; P) + \sigma_{\mu\nu} k_\mu P_\nu H_\pi(k; P) \right]
\]

- Dressed-quark propagator

\[
S(p) = \frac{1}{i\gamma \cdot p A(p^2) + B(p^2)}
\]

- Axial-vector Ward-Takahashi identity entails

\[
f_\pi E_\pi(k; P = 0) = B(k^2)
\]

Owing to DCSB & Exact in Chiral QCD

Miracle: two body problem solved, almost completely, once solution of one body problem is known
Rudimentary version of this relation is apparent in Nambu’s Nobel Prize work.

\[ f_\pi E_\pi(p^2) = B(p^2) \]

The most fundamental expression of Goldstone's Theorem and DCSB in SM.
Rudimentary version of this relation is apparent in Nambu’s Nobel Prize work.

\[ f_\pi \ E_\pi(p^2) \leftrightarrow B(p^2) \]

Pion exists if, and only if, mass is dynamically generated.
The quark level Goldberger-Treiman relation shows that DCSB has a very deep and far reaching impact on physics within the strong interaction sector of the Standard Model; viz.,

Goldstone's theorem is fundamentally an expression of equivalence between the one-body problem and the two-body problem in the pseudoscalar channel.

This emphasises that Goldstone's theorem has a pointwise expression in QCD.

Hence, pion properties are an almost direct measure of the dressed-quark mass function.

Thus, enigmatically, the properties of the massless pion are the cleanest expression of the mechanism that is responsible for almost all the visible mass in the universe.

This algebraic identity is why QCD’s pion is massless in the chiral limit.
Spectrum & Structure of Baryons
Poincaré covariant Faddeev equation sums all possible exchanges and interactions that can take place between three dressed-quarks

Confinement and DCSB are readily expressed

**Prediction**: owing to DCSB in QCD, strong diquark correlations exist within baryons

Diquark correlations are not pointlike
- Typically, $r_{0^+} \sim r_\pi$ & $r_{1^+} \sim r_\rho$ (actually 10% larger)
- They have soft form factors
Computations underway. First results available.

Diquark clustering skews the distribution toward the dressed-quark bystander, which therefore carries more of the proton’s light-front momentum.

Conformal limit:
\[ 120 x_1 x_2 x_3 \]
\[ \langle x_i \rangle = \frac{1}{3} \ldots \text{peak of the distribution} \]

Realistic, finite size (0.7fm)
0\(^+\) diquark \([u(x_2)d(x_3)]\)

Pointlike 0\(^+\) diquark
\([u(x_2)d(x_3)]\)
Light-cone distribution amplitudes of the nucleon and negative parity nucleon resonances from lattice QCD

Light-cone distribution amplitudes of the baryon octet
G. S. Bali et al. JHEP 1602 (2016) 070

- First IQCD results for $n=0, 1$ moments of the leading twist PDA of the nucleon are available

- Used to constrain strength ($a_{11}$) of the leading-order term in a conformal expansion of the nucleon’s PDA:

$$\Phi(x_1, x_2, x_3) = 120 x_1 x_2 x_3 \left[ 1 + a_{11} P_{11}(x_1, x_2, x_3) + \ldots \right]$$

- Shift in location of central peak is consistent with existence of diquark correlations within the nucleon
Nucleon Resonances

Craig Roberts. CLAS & Continuum QCD
Prediction and measurement of ground-state elastic form factors is essential to increasing our understanding of strong-interaction.

However, alone, it is insufficient to chart the infrared behaviour of the strong interaction.
- The hydrogen ground-state didn’t give us QED.

There are numerous nucleon → resonance transition form factors.
- The challenge of mapping their $Q^2$-dependence provides a vast array of novel ways to probe the infrared behaviour of the strong interaction, including the environment and energy sensitivity of correlations.
- Jones-Scadron convention – simplest direct link to helicity conservation in pQCD
- Single set of inputs ...
  - dressed-quark mass function (same as that which predicted meson properties)
  - diquark amplitudes, masses, propagators
  - same current operator for elastic and transition form factors
- Prediction $N \rightarrow \Delta$ transition is indistinguishable from data on $Q^2 > 0.7 \text{ GeV}^2$

Craig Roberts. CLAS & Continuum QCD
Roper Resonance
Constituent-Quark Model brought order to Particle Zoo in the ‘60s

But, the “Roper Resonance” didn’t fit the pattern. It baffled nuclear and particle physicists for more than 50 years.

Discovered in 1963 by L. David Roper while working on his Ph.D. at M.I.T. The Roper is just like the proton, except 50% heavier.

1\textsuperscript{st} problem was its \textit{mass}: until recently, it could not be explained from QCD by any available theoretical method.

EBAC/Argonne-Osaka pushed nuclear physics towards a solution

- Highly advanced, dynamical coupled channels analysis of resonance production: $\gamma N$, $\pi N$, $\eta N$, $K\Lambda$, $K\Sigma$, $\pi\Delta$, $\sigma N$, $\rho N$
- Excellent description of 22,348 \textit{independent data points}, representing \textit{complete array of partial waves}
Argonne-Osaka:

- **Bare Roper state must be included in the DCC analysis**
- **Without it, impossible to achieve description of all available data**
- Bare mass = 1.76 GeV
- Adding Meson-Baryon FSIs, this bare state metamorphoses into three distinct features in the P11 partial wave = two associated with the “Roper” and the third with N*(1710)

DSE prediction for mass of the quark core of the nucleon’s first radial excitation = 1.73 GeV

**Agreement between two completely unrelated approaches to the same problem is very unlikely to be an accident**
An explanation of how and where the Roper resonance fits into the spectrum of hadrons cannot rest on a description of its mass alone.

Instead, it must combine a prediction of the Roper mass with detailed descriptions of its structure and how that structure is revealed in the momentum dependence of the transition form factors.

Moreover, it must combine all this with a similarly complete picture of the proton, from which the Roper resonance is produced.

Last decade ⇒ precise data on $p \rightarrow \text{Roper}$ electroproduction transition form factors, reaching to momentum transfers $Q^2 \approx 4 \text{ GeV}^2$.

This scale probes into domain upon which valence-quark degrees-of-freedom could be expected to determine their behaviour.

Real Test: Unified description of proton, $\Delta$, Roper, and their associated electromagnetic form factors (elastic and transition)
Precisely same framework as employed for nucleon and $\Delta$; viz.
- dressed-quark mass function
- diquark amplitudes, masses, propagators
- same current operator for elastic and transition form factors

$M_{\text{radial-QQQ}} = 1.73 \text{ GeV}$ ... amplitudes typically possess a zero
⇒ lightest excitation of the nucleon is radial excitation

N.B. Argonne-Osaka $M_{\text{Roper-cloud-removed}} = 1.76 \text{ GeV}$
Precisely same framework as employed for nucleon and Δ; viz.
- dressed-quark mass function
- diquark amplitudes, masses, propagators
- same current operator for elastic and transition form factors

- $M_{\text{Roper}} = 1.73 \text{ GeV}$ ... amplitudes typically possess a zero

Meson-baryon final-state interactions reduce core mass by 20%
Diquark content: Nucleon vs Roper

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<th>Nucleon</th>
<th>Roper</th>
<th>Image-Nucleon</th>
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<td>$P_{J=0}$</td>
<td>62%</td>
<td>62%</td>
<td>30%</td>
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<tr>
<td>$P_{J=1}$</td>
<td>38%</td>
<td>38%</td>
<td>70%</td>
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- "Image"-nucleon = orthogonal solution of Faddeev equation at the Roper mass, with eigenvalue $\lambda > 1$

Roper & Nucleon have same diquark content

- Completely different to prediction of contact-interaction, wherein $P_{J=0} \approx 0$
- With richer kernel, orthogonality of ground and excited states is achieved differently
**Predicted transition form factors**

- Excellent agreement with data on $x>2$ (3)
- Like $\gamma N \rightarrow \Delta$, room for meson cloud on $x<2$ ... appears likely that cloud
  - Is a negative contribution that depletes strength on $0<x<2$
  - Has nothing to do with existence of zero; but is influential in shifting the zero in $F_2^* \text{ from } x=\frac{1}{4} \text{ to } x=1$
  - Is irrelevant on $x>2$ (3)

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**DSE Contact**

**DSE Realistic**

**Inferred meson-cloud contribution**

**Anticipated complete result**

Sophisticated continuum framework for the 3-quark bound-state problem
- all elements possess unambiguous link with analogous quantities in QCD
- no parameters varied in order to achieve success.

No material improvement in these results can be envisaged before either:
- novel spectral function methods introduced in Ref. [1] have been extended and applied to the entire complex of nucleon, $\Delta$ and Roper properties
- or numerical simulations of lattice-regularised QCD become capable of reaching the same breadth of application and accuracy

**Conclusion**

- **Observed Roper resonance is at heart the proton's first radial excitation**
  - Consists of a well-defined dressed-quark core
  - Augmented by a meson cloud that reduces its mass by approximately 20% and materially alters its electroproduction form factors on $Q^2 < m_p^2$
Electromagnetically induced transitions proceed via a nontrivial current.

In two separate ways, this current can be considered as a sum of three distinct terms, \textit{viz.}

- **T1** = diquark dissection:
  - T1A – scalar diquark in both the initial- and final-state baryon
  - T1B – pseudovector diquark in both the initial- and final-state baryon
  - T1C – a different diquark in the initial- and final-state baryon

- **T2** = scatterer dissection:
  - T2A – photon strikes a bystander dressed-quark
  - T2B – photon interacts with a diquark, elastically or causing a transition scalar$\leftrightarrow$ pseudovector
  - T2C – photon strikes a dressed-quark in-flight, as one diquark breaks up and another is formed, or appears in one of the two associated “seagull” terms.
Diquark dissection:

T1A:
\[ \Psi_f = \Psi_i = \text{Scalar} \]

T1B:
\[ \Psi_f = \Psi_i = \text{Pseudovector} \]

T1C:
\[ \Psi_f = \text{Scalar} \& \Psi_i = \text{Pseudovector} \]

or vice versa
Dissecting nucleon transition electromagnetic form factors
Jorge Segovia and Craig D. Roberts, arXiv:1607.04405
[nucl-th], Phys. Rev. C (Rapid Comm.) in press

Photon-nucleon current - T2

Scatterer dissection
Upper panel:
- T1A = 0 because Delta does not possess a scalar diquark = [ud] (No red curve)
- T1B and T1C diagrams contribute equally
- Hence, since [ud] is a larger part of the nucleon’s Faddeev amplitude, terms with a pseudovector diquark {qq} in both p and Delta contribute more strongly to the transition.

Lower panel
- Dominant contributions are those in which the photon strikes a dressed quark
- Hence, magnetic component of transition proceeds predominantly via spin-flip of uncorrelated quark, T2C for [ud] in the proton and T2A for {qq}, with slightly greater transition strength in the latter.
Dominance of T1A & T2A ⇒ this component of the transition proceeds primarily through a photon striking a bystander dressed quark that is partnered by [ud]

– lesser but non-negligible contributions from all other processes.

In exhibiting these features, $F_{1,p}$ shows marked qualitative similarities to the proton’s elastic Dirac form factor.
Overwhelming dominance of T1A & T2A

No other diagram makes a significant contribution.

Photon strikes a bystander dressed quark in association with [ud] in the proton and Roper

Same may be said for the dressed quark core component of the proton’s elastic Pauli form factor.
With $\gamma p \to R^+ \& \gamma n \to R^0$ ... flavour separation

Prediction:
- behaviour similar to that of proton elastic form factors because the diquark content of the proton and its first radial excitation are almost identical.

Both systems, dominant piece of wave functions is $\psi_0$, namely, a $u$ quark with a $[ud]$ correlation

If $\psi_0$ were sole component in both, then $\gamma$-$d$-quark interactions receive a $1/x_N$ suppression on $x_N > 1$
- $d$ quark is sequestered in a soft correlation, whereas a spectator $u$ quark is always available to participate in a hard interaction.

At large $x_N$, therefore, scalar diquark dominance leads one to expect $F_d \sim F_u/x_N$.

Precise details of $x_N$-dependence influenced by presence of $\{qq\}$ correlations ... which guarantees that singly represented quark, too, can participate in hard scattering, but to a lesser extent.
Critical issues:

- Is there an environment sensitivity of DCSB and the dressed-quark mass function?
- Are quark-quark correlations an essential element in the structure of all baryons?
  - E.g. N*(1535)(1/2)- and N*(1520)(3/2)- must involve unnatural-parity diquarks = pseudoscalar and vector diquarks ... Baryons possess far more complex internal structure than nucleon and Δ

Existing feedback between experiment and theory \(\Rightarrow\) no environment sensitivity for the nucleon, Δ-baryon and Roper resonance:

- DCSB in these systems is expressed in ways that can readily be predicted once its manifestation is understood in the pion, and this includes the generation of diquark correlations with the same character in each of these baryons.

Nucleon and Δ elastic and transition form factors

Completing the picture of the Roper resonance

Dissecting nucleon transition electromagnetic form factors

Nucleon and Δ elastic and transition form factors

Completing the picture of the Roper resonance

Dissecting nucleon transition electromagnetic form factors
Epilogue
Conformal anomaly ... *gluons & quarks acquire momentum-dependent masses*, values large in the infrared \( m_g \propto 500 \text{ MeV} \) & \( M_q \propto 350 \text{ MeV} \) ... underlies DCSB, origin of hadron masses: many observable consequences

*Diquarks are a reality* ... their existence does not affect the number of baryon states in any obvious way & their presence leads to many verifiable predictions ... no contradictions yet; but stern tests on the horizon

*Nucleon PDAs* ... programme underway; PDFs ... large-\( x \), theoretically “easy” but \( x \)-dependence harder

– Sound computation of PDAs and PDFs are necessary precursor to reliable computation of GPDs and TMDs

How universal is \( M(p^2) \)? How robust are diquark correlations?

– Electroproduction of baryon resonances is one excellent way to tackle questions such as these ... • *Nucleon \( \rightarrow \) Nucleon ... Nucleon \( \rightarrow \) \( \Delta \) ... Nucleon \( \rightarrow \) Roper ...* understood with no environment sensitivity
  • *meson cloud does not alter level ordering in baryon spectrum*
– *Computation alone can/will reveal verifiable signals in observables*
Three form factors describe $N \rightarrow \Delta$: $G_M^*$, $G_E^*$, $G_C^*$

Ratios $R_{EM} \propto G_E^*/G_M^*$ & $R_{SM} \propto G_C^*/G_M^*$ are a particularly sensitive measure of correlations and dressed-quark orbital angular momentum

Helicity conservation demands that $R_{EM} \rightarrow 100\%$ at some (very large?) $x$.

Available data suggest that it’s not happening yet
Very probably, that’s because pion cloud is masking the zero on the currently accessible domain

Judge that because dressed-quark core results agree very well with Sato-Lee’s meson-undressed electric and Coulomb form factors ... determined from data fits more than 8 years ago ... long before DSE results were available

Roper Resonance

- Ratio of charge radii for the quark+diquark core of the Roper compared with that of the nucleon = 1.8
- Harmonic Oscillator result ($L=0$): $r_{n=1}/r_{n=0} = 1.53$
- Significant angular momentum and spin-orbit repulsion introduced via relativity, which increases size of core, for nucleon and Roper

Ratio of charge radii for the quark+diquark core of the Roper compared with that of the nucleon = 1.8

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Significant angular momentum and spin-orbit repulsion introduced via relativity, which increases size of core, for nucleon and Roper
Confinement in Thessaloniki

Outcome of discussions at Confinement XII

– Agreed position of Bali, Brambilla, Petreczky, Roberts:

➢ The flux tube measured in numerical simulations of lQCD with static quarks has zero relevance to confinement in the purely light-quark realm of QCD.

➢ There is zero knowledge of the strength or extension of a flux tube between a static-quark and any light-quark. Indeed, it is impossible to define such a flux tube. It is impossible to compute or even define a flux-tube between a light-quark source and light-quark sink.

➢ Since the vast bulk of visible matter is constituted from light valence quarks, with no involvement of even an accessible heavy quark, then the flux tube picture is not the correct paradigm for confinement in hadron physics.

➢ Confinement in hadron physics is a dynamical phenomenon, intimately connected with the fragmentation effect. It cannot be comprehended without simultaneously understanding dynamical chiral symmetry breaking, which is the origin of a near-zero mass hadron (pion).