Flavour decomposition of electromagnetic transition form factors of nucleon resonances

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XII Quark Confinement and Hadron Spectrum
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Studies of $N^*$-electrocouplings

A central goal of Nuclear Physics: understand the properties of hadrons in terms of the elementary excitations in Quantum Chromodynamics (QCD): quarks and gluons.

Elastic and transition form factors of $N^*$

Unique window into their quark and gluon structure

Broad range of photon virtuality $Q^2$

Distinctive information on the roles played by DCSB and confinement in QCD

Probe the excited nucleon structures at perturbative and non-perturbative QCD scales

CEBAF Large Acceptance Spectrometer (CLAS@JLAB)

☞ Most accurate results for the electroexcitation amplitudes of the four lowest excited states.
☞ They have been measured in a range of $Q^2$ up to:
  - 8.0 GeV$^2$ for $\Delta(1232)P_{33}$ and $N(1535)S_{11}$.
  - 4.5 GeV$^2$ for $N(1440)P_{11}$ and $N(1520)D_{13}$.
☞ The majority of new data was obtained at JLab.

Upgrade of CLAS up to 12 GeV$^2$ → CLAS12 (commissioning runs are underway)
Non-perturbative QCD: Confinement and dynamical chiral symmetry breaking (I)

**Hadrons, as bound states, are dominated by non-perturbative QCD dynamics**

- Explain how quarks and gluons bind together ⇒ Confinement
- Origin of the 98% of the mass of the proton ⇒ DCSB

**Emergent phenomena**

- **Confinement**
  - Colored particles have never been seen isolated

- **DCSB**
  - Hadrons do not follow the chiral symmetry pattern

**Neither of these phenomena is apparent in QCD’s Lagrangian however!**

*They play a dominant role in determining the characteristics of real-world QCD*

*The best promise for progress is a strong interplay between experiment and theory*
From a quantum field theoretical point of view: Emergent phenomena could be associated with dramatic, dynamically driven changes in the analytic structure of QCD’s propagators and vertices.

Dressed-quark propagator in Landau gauge:

\[ S^{-1}(p) = Z_2(i\gamma \cdot p + m^{bm}) + \Sigma(p) = \left( \frac{Z(p^2)}{i\gamma \cdot p + M(p^2)} \right)^{-1} \]

- Mass generated from the interaction of quarks with the gluon-medium.
- Light quarks acquire a HUGE constituent mass.
- Responsible of the 98\% of the mass of the proton and the large splitting between parity partners.

Dressed-gluon propagator in Landau gauge:

\[ i\Delta_{\mu\nu} = -iP_{\mu\nu}\Delta(q^2), \quad P_{\mu\nu} = g_{\mu\nu} - q_{\mu}q_{\nu}/q^2 \]

- An inflexion point at \( p^2 > 0 \).
- Breaks the axiom of reflexion positivity.
- No physical observable related with.
The quantum equations of motion whose solutions are the Schwinger functions

**Continuum** Quantum Field Theoretical Approach:
- Generating tool for perturbation theory → No model-dependence.
- Also **nonperturbative** tool → Any model-dependence should be incorporated here.

**Poincaré covariant** formulation.

- All momentum scales and valid from light to heavy quarks.
- EM gauge invariance, chiral symmetry, massless pion in chiral limit...

No constant quark mass unless NJL contact interaction.
No crossed-ladder unless consistent quark-gluon vertex.
 Cannot add e.g. an explicit confinement potential.

⇒ modelling only within these constraints!

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Use **scattering equation** (inhomogeneous BSE) to obtain $T$ in the first place: $T = K + KG_0 T$.

**Homogeneous BSE for BS amplitude:**

![Diagram](image)

**Baryons.** A 3-body bound state problem in quantum field theory:

**Faddeev equation in rainbow-ladder truncation**

![Diagram](image)

**Faddeev equation:** Sums all possible quantum field theoretical exchanges and interactions that can take place between the three dressed-quarks that define its valence quark content.
Diquarks inside baryons

The attractive nature of quark-antiquark correlations in a color-singlet meson is also attractive for $\bar{3}_c$ quark-quark correlations within a color-singlet baryon.

Diquark correlations:

- A tractable truncation of the Faddeev equation.
- In $N_c = 2$ QCD: diquarks can form color singlets with are the baryons of the theory.
- In our approach: Non-pointlike color-antitriplet and fully interacting.

Thanks to G. Eichmann.

Diquark composition of the Nucleon and Roper

Positive parity state

- Pseudoscalar and vector diquarks
  - Ignored
  - Wrong parity
  - Larger mass-scales

- Scalar and axial-vector diquarks
  - Dominant
  - Right parity
  - Shorter mass-scales

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One must specify how the photon couples to the constituents within the baryon.

Six contributions to the current in the quark-diquark picture

- Coupling of the photon to the dressed quark.
- Coupling of the photon to the dressed diquark:
  - Elastic transition.
  - Induced transition.
- Exchange and seagull terms.
The $\gamma^* N \rightarrow N$ reaction

Work in collaboration with:

- Craig D. Roberts (Argonne)
- Ian C. Cloët (Argonne)
- Sebastian M. Schmidt (Jülich)

Based on:

Sachs electric and magnetic form factors

$Q^2$-dependence of proton form factors:

$Q^2$-dependence of neutron form factors:

\[ x = \frac{Q^2}{m_N^2} \]
Both CI and QCD-kindred frameworks predict a zero crossing in $\mu_p G_E^p / G_M^p$.

The possible existence and location of the zero in $\mu_p G_E^p / G_M^p$ is a fairly direct measure of the nature of the quark-quark interaction.
A world with only scalar diquarks

The singly-represented $d$-quark in the proton $\equiv u[ud]_{0^+}$
is sequestered inside a soft scalar diquark correlation.

**Observation:**

\[ \text{diquark-diagram} \propto \frac{1}{Q^2} \times \text{quark-diagram} \]

Contributions coming from **u-quark**

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Contributions coming from **d-quark**

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The singly-represented d-quark in the proton is not always (but often) sequestered inside a soft scalar diquark correlation.

 Observation:

\[ P_{\text{scalar}} \sim 0.62, \quad P_{\text{axial}} \sim 0.38 \]
Observations:

- $F_{1p}^d$ is suppressed with respect to $F_{1p}^u$ in the whole range of momentum transfer.
- The location of the zero in $F_{1p}^d$ depends on the relative probability of finding $1^+$ and $0^+$ diquarks in the proton.
- $F_{2p}^d$ is suppressed with respect to $F_{2p}^u$, but only at large momentum transfer.
- There are contributions playing an important role in $F_2$, like the anomalous magnetic moment of dressed-quarks or meson-baryon final-state interactions.
Comparison between worlds (I)

\[ x^2 F_1 \]

\[ \kappa_u^{-1} x^2 F^u_2 \]

\[ x^2 F_1^d \]

\[ \kappa_d^{-1} x^2 F^d_2 \]

\[ x = \frac{Q^2}{M^2_N} \]
Observations:

- Axial-vector diquark contribution is not enough in order to explain the proton’s electromagnetic ratios.

- Scalar diquark contribution is dominant and responsible of the $Q^2$-behaviour of the proton’s electromagnetic ratios.

- Higher quark-diquark orbital angular momentum components of the nucleon are critical in explaining the data.

The presence of higher orbital angular momentum components in the nucleon is an inescapable consequence of solving a realistic Poincaré-covariant Faddeev equation.
The $\gamma^* N \to \text{Roper reaction}$

Work in collaboration with:

- Craig D. Roberts (Argonne)
- Ian C. Cloët (Argonne)
- Bruno El-Bennich (São Paulo)
- Eduardo Rojas (São Paulo)
- Shu-Sheng Xu (Nanjing)
- Hong-Shi Zong (Nanjing)

Based on:

- Submitted to Phys. Rev. C (rapid communications) [arXiv: 1607.04405 [nucl-th]]
Disentangling the Dynamical Origin of $P_{11}$ Nucleon Resonances

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The Roper is the proton’s first radial excitation. Its unexpectedly low mass arise from a dressed-quark core that is shielded by a meson-cloud which acts to diminish its mass.
The bare $N^*$ states correspond to hadron structure calculations which exclude the coupling with the meson-baryon final-state interactions:

$$M_{Roper}^{\text{DSE}} = 1.73 \text{ GeV} \quad M_{Roper}^{\text{EBAC}} = 1.76 \text{ GeV}$$

Observation:
- Meson-Baryon final state interactions reduce dressed-quark core mass by 20%.
- Roper and Nucleon have very similar wave functions and diquark content.
- A single zero in $S$-wave components of the wave function $\Rightarrow$ A radial excitation.

0th Chebyshev moment of the $S$-wave components
Observations:

- Our calculation agrees quantitatively in magnitude and qualitatively in trend with the data on $x \gtrsim 2$.
- The mismatch between our prediction and the data on $x \lesssim 2$ is due to meson cloud contribution.
- The dotted-green curve is an inferred form of meson cloud contribution from the fit to the data.
- The Contact-interaction prediction disagrees both quantitatively and qualitatively with the data.
Transition form factors (II)

\[ F_1^* \]

\[ F_2^* \]

\[ A_{1\to R}^{N\to R} \ (10^{-3} \text{ GeV}^{-1/2}) \]

\[ S_{1\to R}^{N\to R} \ (10^{-3} \text{ GeV}^{-1/2}) \]

\[ x = Q^2/m_N^2 \]

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The $\gamma_vp \rightarrow R^+$ Dirac transition form factor

Observations:

- The Dirac transition form factor is primarily driven by a photon striking a bystander dressed quark that is partnered by a scalar diquark.
- Lesser but non-negligible contributions from all other processes are found.
- In exhibiting these features, $F_{1,p}^*$ shows marked qualitative similarities to the proton’s elastic Dirac form factor.
Observations:

- A single contribution is overwhelmingly important: photon strikes a bystander dressed-quark in association with a scalar diquark.
- No other diagram makes a significant contribution.
- $F^*_{2,p}$ shows marked qualitative similarities to the proton’s elastic Pauli form factor.
Obvious similarity to the analogous form factor determined in elastic scattering

The $d$-quark contributions of the form factors are suppressed with respect to the $u$-quark contributions.
Quantum Field Theory view of a baryon:

- Poincaré covariance demands the presence of dressed-quark orbital angular momentum in the baryon.

- Dynamical chiral symmetry breaking and its correct implementation produces pions as well as strong electromagnetically-active diquark correlations.

The $\gamma^* N \to Nucleon$ reaction:

- The presence of strong diquark correlations within the nucleon is sufficient to understand empirical extractions of the flavour-separated form factors.

- Scalar diquark dominance and the presence of higher orbital angular momentum components are responsible of the $Q^2$-behaviour of $G_E^P/G_M^P$ and $F_2^P/F_1^P$.

The $\gamma^* N \to Roper$ reaction:

- The Roper is the proton’s first radial excitation. It consists on a dressed-quark core augmented by a meson cloud that reduces its mass by approximately 20%.

- Our calculation agrees quantitatively in magnitude and qualitatively in trend with the data on $x \gtrsim 2$. The mismatch on $x \lesssim 2$ is due to meson cloud contribution.

- Flavour-separated versions of transition form factors reveal that, as in the case of the elastic form factors, the $d$-quark contributions are suppressed with respect the $u$-quark ones.