Overview of Photoproduction Physics at Jefferson Lab

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Thomas Jefferson National Accelerator Facility

QCD Machine: Electromagnetic Probes of Hadron Structure

JLab in Newport News, VA

- Superconducting RF electron linacs with up to 5 times recirculation
- Up to 1.1 GeV energy gain per pass

6-GeV Era: 1995 - 2012

- C.W. electron beam: 2-ns wide bunch period, 0.2-ns bunch length
- Polarized Source: $P_e \sim 86\%$
- Beam energies up to $E_0 = 6$ GeV
- Beam Current up to 200 $\mu$A
• C.W. electron beam: 2-ns wide bunch period, 0.2-ps bunch length
• Polarized Source: $P_e \sim 85\%$
• Beam energies up to $E_0 = 11 \, (12) \, \text{GeV}$
• Beam Current up to 85 µA
Thomas Jefferson National Accelerator Facility

Detector Systems

Hall A
- High-resolution spectrometers
- Specialized installations

Hall B
- CLAS12
- Large acceptance
  \[ L = 10^{35} \text{ s}^{-1} \text{cm}^{-2} \]

Hall C
- Super-high-momentum spectrometer
  \[ L = 10^{38} \text{ s}^{-1} \text{cm}^{-2} \]

Hall D
- GlueX
- 9-GeV tagged \( \gamma \) beam
- 4\( \pi \) hermetic detector
JLab Photoproduction Scientific Program

Probing Hadron Structure and Strong Interaction with Real and Virtual Photons

- The Hadron Spectra as Probes of QCD (Halls B, D)
  - Baryon and Meson Spectroscopy
- The Transverse Structure of Hadrons (Halls A, B, C, D)
  - Elastic Form Factors
  - Transition Form Factors
- The Longitudinal Structure of Hadrons (Halls A, B, C)
  - Unpolarized and Polarized Parton Distribution Functions
- The 3D Structure of Hadrons (Halls A, B, C)
  - Generalized Parton Distributions (GPDs)
  - Transverse Momentum Distributions (TMDs)
- Hadrons and Cold Nuclear Matter (Halls A, B, C)
  - Nucleon Medium Modifications; Quark Hadronization
  - NN Correlations; Hypernuclear Spectroscopy; Few-Body Experiments
  - Near Threshold J/ψ Photoproduction
- Heavy Photon Search
Hadron Spectroscopy
Quark Models

- **Constituent Quark Models** predict many more of excited states than have been observed; some of the states may only couple weakly to $\pi N$.
- Quark-Diquark Models with a tightly bound diquark predict fewer states.
- Quark and Flux-Tube Models predict increased number of states.

Polarization observables give access to reaction amplitudes

\[ \vec{\gamma}n \rightarrow K^0 \bar{\Lambda} \]: Four complex amplitudes describe the reaction

\[
\frac{d\sigma}{d\Omega} \sim |N|^2 + |S_1|^2 + |S_2|^2 + |D|^2
\]

\[
C_z \frac{d\sigma}{d\Omega} \sim |S_2|^2 - |S_1|^2 - |N|^2 + |D|^2
\]

\[
P \frac{d\sigma}{d\Omega} \sim 2 \text{Im}(S_2 N^* - S_1 D^*)
\]

Baryon Spectroscopy

Extracting Nucleon-Resonance Information from Experimental Data

Database of Experimental Observables
\( \gamma^{(*)}N \rightarrow \pi N, \pi \pi N, \eta N, \eta'N, KY, \rho N, ... \)
\( \pi N \rightarrow \pi N, \pi \pi N, \eta N, \eta'N, KY, \rho N, ... \)

Amplitude Analysis

Dynamical Reaction Theory

N* Properties

Models

LQCD

QCD
Baryon Spectroscopy

Examples of New Data (CLAS) \( \bar{\gamma}(n) \rightarrow K^0\bar{\Lambda} \)

\[
\frac{d\sigma}{d\cos\theta_K^{CM}} [\mu b] \\
\]

\( W [GeV] \)

\( \cos\theta_K^{CM} \)

\( C_z \)

\( B < 0.0 \)  
\( 1.0 \times 10^{-1} \)  
\( 1.1 \times 10^{-1} \)  
\( 1.2 \times 10^{-1} \)

\( 1.3 < E < 1.4 \)  
\( 1.4 < E < 1.5 \)  
\( 1.5 < E < 1.6 \)  
\( 1.6 < E < 1.7 \)

\( 1.7 < E < 1.8 \)  
\( 1.8 < E < 1.9 \)  
\( 1.9 < E < 2.0 \)  
\( 2.0 < E < 2.1 \)

\( 2.1 < E < 2.2 \)  
\( 2.2 < E < 2.3 \)  
\( 2.3 < E < 2.4 \)  
\( E > 2.4 \)

C. Gleason (USC), 2017

\( C_z \) data not fit yet

N. Compton et al. (CLAS Collaboration), submitted to PRC, 2017
Precision data on exclusive photoproduction of light-quark pseudo-scalar and vector mesons:

- Evidence for $N(1900)3/2^+$ (upgraded to *** in PDG).
- $N(1710)1/2^+$ is upgraded to **** in PDG.
- Evidence for $\Delta(2200)7/2^-$ with mass 2180 (parity partner of $\Delta(1950)7/2^-$).
- Evidence for the “missing” $N(2000)5/2^+$
- Other states: $N(1880)1/2^+$, $N(1860)5/2^+$, $N(1895)1/2^-$, $N(1875)3/2^-$, $N(2060)5/2^-$, $N(2150)3/2^-$, $\Delta(1940)3/2^-$. 
- Spin-parity measurement of $\Lambda(1405)$ 

Resonance ratings in PDG: * (evidence of existence is poor), ** (Evidence of existence is only fair), *** (Existence is very likely, but further confirmation of decay modes is required), **** (Existence is certain and properties are at least fairly well explored).
Baryon Spectroscopy

12-GeV Program

• Study of hybrid excitations in the light-quark baryon spectrum: $|qqqg\rangle$. E12-16-010.

• Study of $S=-2, -3$ baryons: spin-parity measurements, search for excited $\Omega^-$ states, new and missing $\Xi$ states, ...

• Study of charm pentaquark states $P_c(4450), P_c(4380)$ via $P_c \rightarrow J/\psi+p$ decay

  - Hall B: tagged and untagged quasi-real photoproduction techniques (expected $\sim 98 \ P_c(4450)$ events/day). Extension of E12-12-001.

  - Hall A: untagged real photoproduction (expected $\sim 70 \ P_c(4450)$ events/day). E12-16-007.
There is an exotic state that appears at a very heavy mass above 3 GeV. Such a state does not arise with a chromomagnetic gluonic excitation combined with $q\overline{q}$ and most likely signals the mass-scale for a different type of gluonic excitation, possibly one having $J^P_g = 1^-$. We note here that the energy ordering of $J^P_g$ as $1^- < 1^+ < ...$ is the same as is observed for gluelumps, the excitations of the gluonic field around a color-octet source in SU(3) Yang-Mills theory. 

C. Isoscalar mesons and kaons

So far we have identified $J^{PC}$ supermultiplets within the isovector meson spectrum but have not considered flavor partners in a flavor multiplet. We expect there to be kaonic and isoscalar states within flavor octets and singlets associated with the isovector states. Kaons have a denser spectrum described by the more limited $J^P$ quantum numbers, the flavored states not being eigenstates of charge conjugation (or the $G$-parity extension). An immediate consequence of this is that there are no exotic kaons, and hence no smoking gun signature for hybrid kaons. Within simple $q\overline{q}$ models, the spectrum of kaons features states constructed from admixtures of opposite $C$, for example, in the axial ($1^+$) sector, one would expect two low-lying states constructed from the basis states $\frac{1}{2} \sin^2 \theta$, $\sin^2 \theta$. Experimentally, two states are found, the $K_1(1270)$, $K_1(1400)$, whose decay properties suggest that they are strong admixtures of the above basis states, with a mixing angle close to 45°. 

LQCD prediction of the light-quark meson spectrum: $q\overline{q}$, $q\overline{q}g$, glueball

CLAS12 (Hall B) and GlueX (Hall D) will probe the mass range 2.0 - 2.5 GeV for such states via exclusive meson photoproduction and multi-particle final states, followed by Partial-Wave Analysis.
Transition Form Factors
More than 98% of the constituent-quark (N/N*) mass is generated non-perturbatively through its coupling to a low-momentum pion cloud. The Higgs mechanism accounts for less than 2% of the N (N*) mass. Momentum dependence of the constituent-quark mass reflects the transition from confinement to asymptotic freedom.
Contributions have been described successfully in dynamical meson-baryon models \[50\] and in e...

The comparison of charge densities on the light cone in transverse impact parameter space (\[41; 42; 43; 44; 45; 46\]). For these two states advanced relativistic quark model calculations \[47\] have recently become available, for the first time employing QCD-based modeling of the excitation of the quark core.

There is agreement with the data at lower mass in LF RQM \[48\] and Light Cone sum rule \[49\] have recently become available for a few years but remain to be fully incorporated in multi-channel partial wave analyses. The light-quark baryon spectrum is likely also populated with hybrid states with pseudoscalar mesons (e.g. \(N(1440)\)) supermultiplets have been studied. The \(N^*(1535)\) and develops a larger shift in the transition is now well measured \[39; 40\]. Two of the prominent higher mass states, the Roper resonance \(N(1440)\) and \(N(1535)\) have been employed with CLAS, leading to new insights into the scale dependence of event degrees of freedom, e.g. meson-baryon, constituent quark, and dressed quark contributions. Several excited states, shown in Fig. 7 assigned to their primary \(N\), \(N^\star\), and \(\Delta^\star\) states. The Roper state has a softer positive core and a wider negative outer cloud than the \(N^\star(1535)\) and \(\Delta^\star(1700)\). Data are measured: differential, total cross sections, polarizations.

Reaction models used: obtain \(\gamma^*NN^*(Q^2)\) electro-couplings

Decomposition: \(\sigma_L, \sigma_T, \sigma_{TT}, \sigma_{LT}, \sigma_{LT}\) and \(N\pi\) loops to model MB cloud: running quark mass in Light-Front (LF) Relativistic QM. I. G. Aznauryan, V.D. Burkert PR C 85 (2012) 055202.

\(N\sigma\) loops to model MB cloud: frozen constituent-quark mass in LF RQM. I. T. Obukhovsky et al. PRD 89, (2014) 0140032.


Meson Baryon cloud inferred from CLAS data as the difference between data and the quark-core evaluation in DSE/QCD. V. Mokeev et al., PR C 93 (2016) 025206.

CLAS12 Program: E12-09-003, E12-06-108A, E12-16-010, E12-16-010A
Elastic Form Factors
Proton electric-charge distribution is different from its magnetization distribution.

**FIGURE 1.**
On the left all recoil polarization results for $\mu_p G_E$/$G_M$; also included are selected Rosenbluth results (empty circles). On the right all polarization results $\mu_n G_E$/$G_M$; also included are older Rosenbluth separation results. In both figures the solid and dashed lines are the results of the VMD calculations of Lomon and Bijker, Refs. [9, 10].

**FIGURE 2.**
The perturbative QCD behavior of the Fermi and Dirac form factor ratio for proton on the left, neutron on the right; a slow down of the rise is visible for the proton; the data is too limited to decide for the neutron.

With the further assumption of isospin symmetry for the corresponding $u$ and $d$ quark form factors, implying:

$$F_{d1}^n = F_{u1}^p$$ and $$F_{u1}^n = F_{d1}^p,$$

and similar relations for $F_2$, the flavor separated $u$ and $d$ quark form factors in the nucleons are linear combinations of the measured form factors $F_1^p, n$ and $F_2^p, n$:

$$F_{u1}^n = \frac{2}{3} F_1^p + \frac{1}{3} F_1^n$$ and $$F_{d1}^n = F_1^p + \frac{2}{3} F_1^n,$$

$$F_{u2}^n = \frac{2}{3} F_2^p + \frac{1}{3} F_2^n$$ and $$F_{d2}^n = F_2^p + \frac{2}{3} F_2^n.$$
Two-Photon-Exchange Mechanism

Proposed to explain the difference between proton FF ratio from cross-section and from polarization data

![Diagram of Two-Photon-Exchange Mechanism]

TPE Corrections
- sizeable for the cross-section data (Rosenbluth separation)
- very small (≤3% at 5.5 GeV²) for the polarization-ratio data

![Graphs showing comparison of polarization measurements (filled diamonds) and LT separations (open circles) with no TPE corrections (left), TPE corrections from a fit combining previous cross section measurements with new low-Q² data (center), and with the additional high-Q² correction (right)].

Comparison of precise Rosenbluth and Polarization measurements of effect on cross section

Polarized proton form factor measurements

Proposed to explain the difference between proton FF ratio from cross-section and from polarization data

Two-Photon-Exchange Correction

Directly Accessed Experimentally in $e^+p$ vs $e^-p$ Elastic Scattering

\[ R = \frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx \frac{1 + \delta_{even} - \delta_{2\gamma} - \delta_{e.p.brems}}{1 + \delta_{even} + \delta_{2\gamma} + \delta_{e.p.brems}} \approx \frac{1 - 2(\delta_{2\gamma} + \delta_{e.p.brems})}{1 + \delta_{even}}, \quad R_{2\gamma} \approx 1 - 2\delta_{2\gamma} \]

The CLAS TPE Experiment

Extracted correction applied to $e^-p$ cross section ($Q^2=1.75$ GeV$^2$), followed by Rosenbluth separation

- $\mu_p G_E/G_M = 0.910\pm0.060$, uncorrected
- $\mu_p G_E/G_M = 0.837\pm0.066$, TPE corrected; consistent with polarization-ratio value of $0.789\pm0.042$

Near-Threshold $J/\psi$ Photoproduction
Near-Threshold $J/\psi$ Photoproduction at 12 GeV

Probing Non-Perturbative Gluon Fields in the Proton

- $E_{\gamma,\text{thr}}=8.20$ GeV, $|t_{\text{min}}|=1.7$ GeV$^2$: small transverse-size probe ($r_\perp \sim 1/m_c=0.13$ fm), small impact parameter ($b \sim 1/|t|^{1/2} \sim 0.2$ fm).

- Reaction cross section sensitive to short-distance dynamics in the proton and multi-gluon exchange mechanisms; $J/\psi$-N cross section

\[ \text{FIG. 2: Variation of the } J/\psi \text{ photoproduction cross section near threshold. Solid line: two gluon exchange. Dashed line: three gluon exchange [10].} \]

- Vigorous Program:
  - Proton Target:
    - CLAS12: E12-12-001
    - Hall A: PR12-12-006
    - Hall C: E12-16-007
  - Nuclear Targets:
    - Hall C: PR12-07106
  - Planned d target:
    - CLAS12: LOI2017
Near-Threshold $J/\psi$ Photoproduction at 12

The very first $J/\psi$ Detected at JLab with GlueX

- Exclusive measurement of $\gamma p \rightarrow J/\psi + p, J/\psi \rightarrow e^+ e^-$ (all final-state particles detected)
- Kinematic fit using tagged-photon energy; $e^+ e^-$ PID using calorimeters
- Data from first (engineering) run in 2016

MC normalized to $\phi$ x-section.

kin.fit $\chi^2 < 200$, $\theta_e > 2^\circ$

$J/\psi \sim 100$ events

$\sigma = 9 \pm 1$ MeV

L. Pentchev, Private Communication, 2017
Near-Threshold J/ψ Photoproduction at 12

The very first J/ψ Detected at JLab with GlueX

• First time cross-section measurements down to the threshold, sensitive to gluons at high x
• Can set limits on pentaquark Pc(4450) yield (6 MeV mass resolution)

L. Pentchev, Private Communication, 2017
Summary

JLab Photoproduction Scientific Program

• Baryon Resonances
  – CLAS has been providing precision observables on exclusive meson photoproduction off the nucleon leading to the discovery of several new states and the confirmation of poorly known states.
  – Exclusive electro-production data have provided new insight into the scale dependence of effective degrees of freedom of resonances.
  – Extensive program for studies of hybrid, \( S=-2, -3 \) resonances at 12 GeV

• Meson Spectroscopy
  – Studies of hybrid and exotic mesons with GlueX and CLAS12

• Elastic Proton Form Factors
  – Are a highlight of the 6-GeV program; Show importance of 2-photon exchange mechanisms; Extended studies at 12 GeV.

• Near Threshold \( J/\psi \) Photoproduction off proton, deuteron, and heavier targets: non-perturbative gluon dynamics, \( J/\psi-N \) cross section, charm pentaquarks.
Backup Slides
LQCD predicts states with the same quantum numbers as CQMs with underlying SU(6) x O(3) symmetry; more states than have been identified experimentally.

# Near-Threshold J/ψ Production at JLab 12

## Approved Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam</th>
<th>Target</th>
<th>Detector</th>
<th>Detect</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR12-12-001</td>
<td>γ (QR)</td>
<td>p</td>
<td>CLAS12</td>
<td>e⁺, e⁻, p</td>
<td>120</td>
</tr>
<tr>
<td>PR12-12-006</td>
<td>e⁻</td>
<td>p</td>
<td>SoLID</td>
<td>e⁺, e⁻, p, e⁺, e⁻, e'</td>
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</tr>
<tr>
<td>PR12-16-007</td>
<td>γ (R)</td>
<td>p</td>
<td>Hall C</td>
<td>e⁺, e⁻</td>
<td>11</td>
</tr>
<tr>
<td>PR12-07-106</td>
<td>γ (QR)</td>
<td>p, d, Be, Ca, Al, Cu, Ag, Au</td>
<td>Hall C</td>
<td>e⁺, e⁻, µ⁺, µ⁻</td>
<td>CA</td>
</tr>
</tbody>
</table>
CLAS12 Detector Overview

- General
  - 11 GeV polarized electron beam
  - Luminosity: $10^{35} \text{ cm}^{-2}\text{s}^{-2}$

- Forward Detector (toroidal spectrometer)

<table>
<thead>
<tr>
<th>Charged Tracks</th>
<th>Neutral Tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ang. Acceptance: 5° - 35°</td>
<td>Ang. Acceptance: 5° - 40° (neutron)</td>
</tr>
<tr>
<td>0.5% - 1% for 5 GeV track</td>
<td>Energy resolution: $&lt; 0.1/\sqrt{E}$</td>
</tr>
<tr>
<td>1 mrad for the electron track</td>
<td>&lt; 4 mrad</td>
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</tbody>
</table>

- Central Detector (solenoid magnet): momentum range: 0.3 - 1.3 GeV/c

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<tr>
<td>Ang. Acceptance: 35° - 125°</td>
<td>40° - 125° (neutron)</td>
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<tr>
<td>5% for 1 GeV track</td>
<td>Energy resolution: &lt; 5%</td>
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<tr>
<td>5 - 10 mrad</td>
<td>&lt; 10 mrad</td>
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