Highlights on hadron physics at CLAS

K. Hicks (Ohio U.)
Hadron 2011 Conference
June 16, 2011
Outline

• Meson-Baryon Cloud (MBC) Effects
  – New results on baryon photocouplings
  – Need for coupled-channels analysis

• Spectroscopy of baryons and mesons
  – New and future analysis of $K\Lambda$
  – New data: $2\pi$, $K^*Y$, $KY^*$, etc.

• Future upgrade to CLAS12
  – Probe transition from MBC to quark core.
Quark mass extrapolated to the chiral limit, where $q$ is the momentum variable of the tree-level quark propagator (curve=DSE, data=LQCD).

- Resolution
- Low
- High

3q-core+MB-cloud

pQCD

meson dressed quark

LQCD, DSE and …

confinement

current quark
In the relativistic QM framework, the bare-core contribution is well described by the three-quark component of the wavefunction.

One third of $G_M^*$ at low $Q^2$ is due to contributions from meson–baryon (MB) dressing:

The area of $Q^2<7.0$ GeV$^2$ is far from pQCD domain.

B. Julia-Diaz et al., PRC 69, 035212 (2004)
Dynamical coupled-channels model of EBAC


✓ Partial wave (LSJ) amplitude of a → b reaction:

\[ T_{a,b}^{(LSJ)}(p_a, p_b; E) = V_{a,b}^{(LSJ)}(p_a, p_b) + \sum_c \int_0^\infty q^2 dq V_{a,c}^{(LSJ)}(p_a, q)G_c(q; E)T_{c,b}^{(LSJ)}(q, p_b; E) \]

coupled-channels effect

✓ Reaction channels:

\[ a, b, c = (\gamma^{(*)}N, \pi N, \eta N, \pi \Delta, \sigma N, \rho N, K\Lambda, K\Sigma, \cdots) \]

\[ \pi \pi N \]

✓ Transition potentials:

\[ V_{a,b} = v_{a,b} + \sum_{N^*} \frac{\Gamma_{N^*,a}^{\dagger} \Gamma_{N^*,b}^{\dagger}}{E - M_{N^*}} \]

Meson-exchange potentials
(Derived from Lagrangians)

bare N* states
Partial wave (LSJ) amplitude of a $a \rightarrow b$ reaction:

Reactions channels:

Transition potentials:

Dynamical coupled-channels model of EBAC

Physical $N^*$s will be a “mixture” of the two pictures:

$$|N^*\rangle = |MB\rangle$$

$$|N^*\rangle = |qqq\rangle + |\text{m.c.}\rangle$$


$$V_{a,b} = v_{a,b} + \sum_{N^*} \frac{\Gamma_{N^*,a}^\dagger \Gamma_{N^*,b}}{E - M_{N^*}}$$

exchange potentials of ground state mesons and baryons

bare $N^*$ states
Jefferson Lab Today

Large acceptance spectrometer
electron/photon beams

Hall B

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Radiative Decay of Strange Baryons
General Motivation

• Electromagnetic interactions are the cleanest way to access information on wavefunctions.
  – For strange baryons, the EM coupling can only be studied by measuring the decay.

• SU(6) wavefunctions provide a zeroth-order prediction for M1 transitions.
  – SU(6) symmetry provides a link between N* and Y* radiative decays: constrain SU(6) symmetries.
U-spin: connects $\Delta$ and $\Sigma^*$ decays

• SU(3) has three equal symmetries:
  – I-spin: exchange of u and d quarks
  – U-spin: exchange of d and s quarks
  – V-spin: exchange of u and s quarks

• With respect to known symmetries:
  – I-spin conserves chiral symmetry (mass)
  – U-spin conserves EM symmetry (charge)
  – V-spin conserves neither chiral nor EM symmetry
Group structure of U-spin:

\[ SU(3)_f \supset SU(2)_I \times U(1)_Y \supseteq SU(2)_U \times U(1)_Q \]
How is this useful?

It is possible using the U-spin SU(3) multiplet representation to obtain a prediction for the ratio of the $\Delta^0 \to n\gamma$ partial width to the $\Sigma^{*0} \to \Lambda\gamma$ partial width.

$$\langle \Delta^0 | n\gamma \rangle = \langle 1 \ 1 \ 1 \ 0 \ 0 \ 0 \rangle = 1$$

$$\langle \Sigma^{*0} | \Lambda\gamma \rangle = -\frac{\sqrt{3}}{2} \langle 1 \ 0 \ 1 \ 0 \ 0 \ 0 \rangle = -\frac{\sqrt{3}}{2},$$

leading to a ratio;

$$\frac{|\langle \Delta^0 | n\gamma \rangle|^2}{|\langle \Sigma^{*0} | \Lambda\gamma \rangle|^2} = \frac{4}{3},$$

including phase space factors (PRD 28 (1983) 1125)

$$\frac{\Gamma(\Delta^0 \to n\gamma)}{\Gamma(\Sigma^{*0} \to \Lambda\gamma)} = \left( \frac{M_n}{M_\Delta} \right) \left( \frac{M_\Lambda}{M_{\Sigma^{*0}}} \right)^{-1} \left( \frac{q_n}{q_\Lambda} \right)^3 \frac{4}{3} = 1.56.$$
The final calculated ratio with all uncertainties is

\[ R_{\Lambda^0\pi}^{\Lambda\gamma} = \frac{\Gamma[\Sigma^0(1385) \to \Lambda\gamma]}{\Gamma[\Sigma^0(1385) \to \Lambda\pi^0]} = 1.42 \pm 0.12^{+0.11}_{-0.07}(\text{sys}) \]

The electromagnetic decay partial width using the full width \( \Gamma = 36 \pm 5 \text{ MeV} \),

\[ \Gamma = 445 \pm 73^{+71}_{-66}(\text{sys}) \text{keV} \]

compared to the previous experimental result by Taylor,

\[ \Gamma = 479 \pm 120^{+81}_{-100}(\text{sys}) \text{keV} \]
# Predictions from other models

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Delta \rightarrow N\gamma$</th>
<th>$\Sigma \rightarrow \Lambda\gamma$</th>
<th>$\Sigma^{*0} \rightarrow \Lambda\gamma$</th>
<th>$\Sigma^{*+} \rightarrow \Sigma^{+}\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRQM[17, 23, 26]</td>
<td>360</td>
<td>8.6</td>
<td>273</td>
<td>104</td>
</tr>
<tr>
<td>RCQM[24]</td>
<td></td>
<td>4.1</td>
<td>267</td>
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<tr>
<td>$\chi$CQM[25]</td>
<td>350</td>
<td></td>
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<td>105</td>
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<tr>
<td>MIT Bag[26]</td>
<td></td>
<td>4.6</td>
<td>152</td>
<td>117</td>
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<tr>
<td>Soliton[27]</td>
<td></td>
<td></td>
<td>243</td>
<td>91</td>
</tr>
<tr>
<td>Skyrme[28, 29]</td>
<td>309-326</td>
<td>157-209</td>
<td></td>
<td>47</td>
</tr>
<tr>
<td>Algebraic model[30]</td>
<td>341.5</td>
<td>8.6</td>
<td>221.3</td>
<td>140.7</td>
</tr>
</tbody>
</table>

**Experiment:**  
660 +/- 60  
479 +/- 73
Interpretation

• Meson-Baryon Cloud effects are substantial for the Y* resonances also.
  – U-spin relation works better than QM, etc.

• We can now make a prediction for $\Sigma^{*+}$ decay.
  – The Wigner-Eckart theorem requires that the branching ratios $\Delta^+ \to p\gamma$ and $\Delta^0 \to n\gamma$ are equal.
  – U-spin predicts a ratio:

\[
\frac{\Gamma(\Delta^+ \to p\gamma)}{\Gamma(\Sigma^{*+} \to \Sigma^{+}\gamma)} = \left( \frac{M_p}{M_\Delta} \right) \left( \frac{M_{\Sigma^+}}{M_{\Sigma^{*+}}} \right)^{-1} \left( \frac{q_p}{q_{\Sigma^+}} \right)^3 = 2.638.
\]
New CLAS result

The final results for the ratio of the $\Sigma^{*+} \to \Sigma^+ \gamma$ to $\Sigma^{*+} \to \Sigma^+ \pi^0$ with systematic uncertainties is

$$R_{\Sigma^{*+} \to \Sigma^+ \gamma}^{\Sigma^{*+} \to \Sigma^+ \pi^0} = \frac{n_\gamma A_\pi(\Sigma\pi) - n_\pi A_\gamma(\Sigma\pi)}{n_\pi A_\gamma(\Sigma\gamma) - n_\gamma A_\pi(\Sigma\gamma)} = 11.95 \pm 2.21^{+0.52}_{-1.21} (\text{stat})^{+0.52}_{-1.21} (\text{sys})\%,$$  \hspace{1cm} (27)

$$\Gamma_{\Delta^+ \to \Sigma^+ \gamma} = R_{\Sigma^{*+} \to \Sigma^+ \gamma}^{\Sigma^{*+} \to \Sigma^+ \pi^0} R(\Sigma^* \to \Sigma^+ \pi^0) \Gamma_{\text{Full}} = 250 \pm 56.9^{+34.3}_{-41.2} (\text{stat})^{+34.3}_{-41.2} (\text{sys})\text{keV}.$$

This implies that the U-spin prediction for the partial width of the electromagnetic decay using the width of the $\Delta^+ \to p\gamma$ decay is,

$$2.638^{-1} \times \Gamma(\Delta^+ \to p\gamma) = 2.638^{-1} \times 660 \pm 60 = 250 \pm 23\text{keV}.$$  \hspace{1cm} (29)
The MBC in electroproduction
N* electrocouplings from analyses of exclusive channels

Separation of resonant/non-resonant contributions

N* ‘s can couple to various exclusive channels with entirely different non-resonant amplitudes, while their electrocouplings should remain the same.

Consistent results from the analyses of Nπ and Nππ electroproduction channels show that model uncertainties are under control.

See the afternoon talk today by Victor Mokeev.
$\gamma_{\nu}NN^*$ electrocouplings from $\Lambda\pi/\Lambda\pi\pi$ production

$\Lambda\pi\pi$ CLAS (New!) preliminary.

$\Lambda\pi$ CLAS


$\Lambda\pi$ world


$\Lambda\pi$ $Q^2=0$, PDG.

$\Lambda\pi$ $Q^2=0$, CLAS


Good agreement between the $\Lambda\pi$ and $\Lambda\pi\pi$ channels.

$N^*$ electrocouplings are measurable and model independent.
High lying resonance electrocouplings from $\pi^+\pi^-p$

Electrocouplings of $S_{31}(1620)$, $S_{11}(1650)$, $F_{35}(1685)$, $D_{33}(1700)$, and $P_{13}(1720)$ states were obtained for the first time from $\pi^+\pi^-p$ electroproduction data.
Mystery of $P_{11}(1440)$ structure is solved

Quark models:
- I. Aznauryan LC
- S. Capstick LC
- Relativistic covariant approach by Ramalho & Gross
- EBAC-DCC MB dressing (absolute values).

The electrocouplings are consistent with $P_{11}(1440)$ structure as combination:
- a) quark core as a first radial excitation of the nucleon, and
- b) meson-baryon dressing.

MBC effects could explain the data at low $Q^2$. 

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Coupled-channels effect in various reactions

- **Pion photoproductions**
- **Pion electroproductions**
- **Double pion productions**

\[ \gamma p \rightarrow \pi^0 p \]
\[ \gamma p \rightarrow \pi^+ n \]
\[ p(e, e' \pi^0) p \]

\[ \pi^- p \rightarrow \pi^+ \pi^- n \]

**EBAC**

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Lineshape of the $\Lambda(1405)$
Chiral Unitary Coupled Channel Approach

dynamically generate $\Lambda(1405)$
based on chiral unitary model

$\gamma p \rightarrow K^+\pi^-\Sigma$
$E_\gamma = 1.7 \text{ GeV}$

Difference in Lineshape

\[
\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{2} |T^{(1)}|^2 + \frac{1}{3} |T^{(0)}|^2 + \frac{2}{\sqrt{6}} \text{Re}(T^{(0)}T^{(1)*}) + O(T^{(2)})
\]

\[
\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{2} |T^{(1)}|^2 + \frac{1}{3} |T^{(0)}|^2 - \frac{2}{\sqrt{6}} \text{Re}(T^{(0)}T^{(1)*}) + O(T^{(2)})
\]

\[
\frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3} |T^{(0)}|^2 + O(T^{(2)})
\]

J. C. Nacher et al., Nucl. Phys. B455, 55

- Difference in lineshapes is due to interference of isospin terms in calculation ($T^{(1)}$ represents amplitude of isospin I term)
- Distortion of the lineshape is connected to underlying QCD amplitudes that generate the $\Lambda(1405)$
- This analysis will measure all three $\Sigma\pi$ channels
Results of Lineshape

- lineshapes do appear different for each $\Sigma \pi$ decay mode
- $\Sigma^+ \pi^-$ decay mode has peak at highest mass, narrow than $\Sigma^- \pi^+$
- lineshapes are summed over acceptance region of CLAS
- difference is less prominent at higher energies

preliminary
Interpretation

• For a baryon resonance with a single pole, isospin symmetry $\rightarrow \Sigma^+\pi^- = \Sigma^-\pi^+$.

• The data favor a dynamically-generated resonance (two-pole solution $\Sigma\pi$ and NK).
  – Evidence of MB coupled-channels effects?
Spectroscopy with KY, K*Y and KY*
Quark Model Classification of N*

Lowest Baryon Supermultiplets
SU(6)xO(3) Symmetry

Particle Data Group
- ****
- ***
- **

\[ \Delta(1232) \]

\[ D_{13}(1520) \]
\[ S_{11}(1535) \]

New \( P_{11}, P_{13}, \) or \( D_{13} \) states?

\[ + q^3g \]
\[ + q^3q\bar{q} \]
\[ + N\text{-Meson} \]
\[ + \ldots \]

Roper \( P_{1\frac{1}{2}}(1440) \)

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Amplitude Uncertainty in $\gamma p \rightarrow K^+\Lambda$

CLAS (g1c, g11a) and GRAAL $\sigma, C_{x'}, C_{z'}, \sigma, P$ and $\Sigma, T, P, O_{x'}, O_{z'}$

Real parts of the PWA multipoles
BoGa (dot-dashed), MAID (dashed), SAID (dotted), JSLT (solid)


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Process is described by 4 complex, parity conserving amplitudes
- 8 well-chosen measurements are needed to determine amplitude
- For hyperon finals state 16 observables will be measured in CLAS ➠ large redundancy in determining the photo-production amplitudes ➠ allows many cross checks
- 8 observables measured in reactions without recoil polarization

### Photon beam | Target | Recoil | Target - Recoil
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td>x'</td>
<td>y'</td>
<td>z'</td>
</tr>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>z</td>
</tr>
<tr>
<td>unpolarized</td>
<td>$\sigma_0$</td>
<td>T</td>
<td>P</td>
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<tr>
<td>linearly $P_\gamma$</td>
<td>$\Sigma$</td>
<td>H</td>
<td>P</td>
</tr>
<tr>
<td>circular $P_\gamma$</td>
<td>F</td>
<td>E</td>
<td>$C_{x'}$</td>
</tr>
</tbody>
</table>
**K*+Y Photoproduction**

**Motivation:**
1. Search for higher-mass N* resonances

2. Compare with KY and K*0Y
   a. K*Y coupling sensitive to K_0(800).
   b. K_0(800) is part of the scalar nonet.
   c. K_0(800) has not been directly observed.

Differential cross sections of $K^{*+}\Lambda$:

1.5 --- 2.1 GeV

2.1 --- 2.7 GeV

Preliminary result

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Differential cross sections of $K^{*+} \Sigma^0$:

1.7 --- 2.3 GeV

2.3 --- 2.9 GeV

Preliminary result

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Total Cross Sections

$$\gamma + p \rightarrow K^{*+} + \Lambda$$

$$\gamma + p \rightarrow K^{*+} + \Sigma^0$$

Preliminary result
\[ \gamma n \rightarrow K^+ \Sigma^* (1385)^- \text{ Cross Section} \]

- Oh, et. al model \[^{[13]}\]: effective Lagrangians, model $\delta \sigma$'s not quoted
- Partially constrained by $\gamma p \rightarrow K^+ \Sigma^*0$ preliminary total cross section \[^{[11]}\]
- Dominated by t-channel $K^+$ and $K^{*+}$, some $N^*$'s and $\Delta^*$'s included
  - $N_{\frac{1}{2}}^-(1945)$, $N_{\frac{3}{2}}^-(1960)$, $N_{\frac{3}{2}}^-(2095)$, $N_{\frac{5}{2}}^-(2095)$, $N_{\frac{5}{2}}^+(1980)$

Legend
- Black: CLAS g13 (preliminary)
- Blue: Oh, et. al Model \[^{[13]}\]
- Red: LEPS \[^{[6]}\]
Meson Spectroscopy
Hybrid Mesons at CLAS

Excitations of the flux tube can give rise to gluonic hybrid mesons

Photoproduction of Hybrid Mesons

Reactions of interest:
- $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$
- $\gamma p \rightarrow K^+ K^- \pi^0$
- $\gamma p \rightarrow p \pi^+ \pi^- \pi^0$
- $\gamma p \rightarrow n K^+ K^- \pi^+$
- $\gamma p \rightarrow p \pi^+ \pi^-$
- $\gamma p \rightarrow p K^+ K^-$

Mass Independent Partial Wave Analysis

$10^3$ Events/20 MeV

$\text{Mass} (\pi^+ \pi^+ \pi^-)$ GeV/c$^2$

Run Conditions:
- 5.74 GeV Electron
- 4.4–5.7 GeV tagged photons
- 30 events/pb sensitivity
- Modified CLAS geometry
- 5x10$^6$/sec photon flux

Jefferson Lab
CEBAF @ 6 GeV

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New: Scalar Mesons from $\gamma p \rightarrow K_s K_s p$

- 4-π Invariant mass (GeV)

**CLAS g11**

- $E_\gamma^{\text{max}} = 3.8$

**f(1500)**

- 4-π Invariant mass (GeV)

**CLAS g12**

- $E_\gamma^{\text{max}} = 5.7$
The future: CLAS12
- Luminosity $> 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
- Hermeticity
- Polarization
- Baryon Spectroscopy
- Elastic Form Factors
- N to N* Form Factors
- GPDs and TMDs
- DIS and SIDIS
- Nucleon Spin Structure
- Color Transparency
- ...

Central Detector

1m

Forward Detector

Torus

LTCC

EC

FTOF

Region 3

Region 2

Region 1

Solenoid

SVT

CTOF

CLAS12

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Forward Photon Tagger for Spectroscopy

Calorimeter + hodoscope + tracker

Electron energy/momentum
Photon energy ($\nu$=E-E')
Polarization $\varepsilon^{-1} \sim 1 + \nu^2/2EE'$

Veto for photons

Electron angles
$Q^2 = 4EE' \sin^2 \theta/2$
Scattering plane

Rates in the forward tagger
$L_e \sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$  ($N_\gamma \sim 5 \times 10^8 \gamma/\text{s}$)
A new N* regime at $Q^2 > 3.5$ GeV$^2$?

Data appear to reach a plateau at $Q^2 > 3.5$ GeV$^2$, but conclusive tests require higher $Q^2$.

Transition to photon interactions with dressed quarks?

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Resonance Transitions at 12 GeV

Experiment E12-09-003 will extend access to transition FF for many prominent states in the range to $Q^2=12\text{GeV}^2$.

Electromagnetic form factors are sensitive to the effective quark mass. At 12 GeV we probe the transition from “dressed quarks” to elementary quarks.

At 12 GeV we probe the transition from “dressed quarks” to elementary quarks.
Summary

• The Meson-Baryon Cloud has significant effects on photon coupling observables
  – We cannot ignore coupled-channel effects!
• There are precise new data on KY, K*Y, KY*
  – This will help the search for missing resonances
  – K* data will determine the role of the $K_0(800)$.
• PWA for mesons: exotics & scalar mixing
• Future: CLAS12: transition to current quarks.
Backup Slides
t-dependence of f(1500)