Hadron Spectroscopy with CLAS and CLAS12

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For the CLAS collaboration

Excited QCD 2015
• Baryon Spectroscopy with CLAS

• Meson Spectroscopy with CLAS12 (2017–...)

Experimental Hall B
15 Years of Physics
Why study hadron spectroscopy

- Strong Interaction responsible for spectrum of hadrons
- QCD provides, in principle, a quantitative description of the strong interaction
- Understanding the spectrum of hadrons in terms of QCD is an important validation

- Can we quantitatively understand quark/gluon confinement?
- Can we determine relevant QCD degrees of freedom?
- Do we understand how these combine to form hadronic states?
A Primary Physics Goal of CLAS

Search for Missing Baryon Resonances

Strategy:

- High Intensity electromagnetic Beam
- Large Acceptance Magnetic Spectrometer
- Many final states (different couplings)
- Beam, Target and Recoil polarisations
- PWA to extract contributing resonances
CLAS follows many paths...

This presentation will focus on a small selection

- Pseudoscaler Meson Photoproduction
- Polarised Target
- Vector Meson Production
- Double Meson Production
- Neutron Target
- Baryon Electroproduction
- Strangeness Photoproduction
- K* and Y*
- Cascade Spectroscopy

Need to achieve a consistent picture
- Intense polarised e-beam

- Large Acceptance Magnetic spectrometer
  - many different final states

$E_{\text{max}} \sim 6 \text{ GeV}$

$I_{\text{max}} \sim 200 \mu\text{A}$

Duty Factor $\sim 100\%$

$\sigma_{E/E} \sim 2.5 \times 10^{-5}$

Beam P $\sim 80\%$

$E_\gamma \sim 0.8 - 5.7 \text{GeV}$
CLAS

CEBAF
Large
Acceptance
Spectrometer

- Large Acceptance Magnetic spectrometer - many different final states
Pseudoscalar Meson Photoproduction

Produce and measure many final states

Often involving intermediate baryon resonances
Pseudoscalar Meson Photoproduction

4 photoproduction amplitudes
16 experimental observables
Contributing resonances
encoded in observables

Dependent on beam, target and recoil polarisations

\[
\frac{d\sigma}{d\Omega} = (\frac{d\sigma}{d\Omega})_{unpol} \left\{ 1 - P_{\gamma}^{lin} \Sigma \cos 2\phi + P_x \left[ P_{\gamma}^{circ} F - P_{\gamma}^{lin} H \sin 2\phi \right] 
+ P_y [T - P_{\gamma}^{lin} P \cos 2\phi] + P_z [- P_{\gamma}^{circ} E + P_{\gamma}^{lin} G \sin 2\phi] \right\}
\]

\[
\rho \frac{d\sigma}{d\Omega} = (\frac{d\sigma}{d\Omega})_{unpol} \left\{ 1 - P_{\gamma}^{lin} \Sigma \cos 2\phi + P'_x \left[- P_{\gamma}^{circ} C_x - P_{\gamma}^{lin} O_x \sin 2\phi \right] 
+ P'_y [P - P_{\gamma}^{lin} T \cos 2\phi] + P'_z [- P_{\gamma}^{circ} C_z - P_{\gamma}^{lin} O_z \sin 2\phi] \right\}
\]

Barker, Donnachie and Storrow
Nuclear Physics B95 (1975) 347
### Single Meson Photoproduction

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### Neutron target

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Example: \( \Sigma \) for \( \pi^0 p \)

Results suggest significant change in couplings for well known \( \Delta(1700) \) and \( \Delta(1700) \)

First Measurement of the Polarization Observable $E$ in the $\bar{p}(\gamma, \pi^+)n$ Reaction up to 2.25 GeV

FIG. 3. (Color online) Double polarization observable $E$ in the $\bar{p}\gamma \rightarrow \pi^+ n$ reaction as a function of $\cos \theta_{\pi cm}$ for three selected bins of the center-of-mass energy $W$. Systematic uncertainties are indicated as shaded bands. The curves in the upper panels are results from the SAID ST14 [10], Jülich14 [9], and BnGa11E [8] analyses. The curves in the lower panels are results from updated analyses including the present $E$ data.

Improved helicity couplings for a number of resonances
Strangeness Photoproduction

- Very precise data on pion photoproduction
- Results consistent with $\pi N$ scattering
- Allowed refinement of $N^*$ properties
- Many additional polarised target data coming soon

- Above 1.4GeV mass, $N^*$ decay to other states increasingly important
- May learn about states with small coupling to $\pi N$
- Use associated strangeness photoproduction
- $\Lambda$ decay gives additional recoil polarisation!
$K^+\Lambda$ cross section and polarisation

M. McCracken et al. (CLAS),
Phys. Rev. C 81, 025201, 2010
K$^+\Lambda$ circular polarisation transfer

Data available for a few years already.

Significant impact on PWA.
$K^+\Lambda$ with Linearly polarised beam (1)

$\gamma + p \rightarrow K^+ \Lambda$

$W=1.72\text{GeV}$

$\gamma + p \rightarrow K^+ \Lambda$

$W=2.18\text{GeV}$

C. Paterson, D. Ireland, K. Livingston, B. McKinnon et al
$K^+ \Lambda$ with Linearly polarised beam (2)

\[ \gamma + p \rightarrow K^+ \Lambda \]

\[ \cos \theta_K \]

C. Paterson, D. Ireland, K. Livingston, B. McKinnon et al
What have we learnt so far...

New resonances from Bonn Gatchina group (includes data from other photo and pion induced reactions)


\[
N(1880)^{\frac{1}{2}^+}, N(1860)^{\frac{5}{2}^+}, N(1895)^{\frac{1}{2}^-}, N(1875)^{\frac{3}{2}^-}, N(2150)^{\frac{3}{2}^-}, \text{and } N(2060)^{\frac{5}{2}^-}
\]

Observation:
Missing Resonances $\rightarrow$ Missing Multiplets

E. Klempt, B. Ch. Metsch,  

Better determination of known resonance properties

With much more data to come


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Meson Spectroscopy with CLAS12

Primary Physics Goal for CLAS12 e-beam
  • Nucleon Structure (not discussed here)
  • But high potential for Meson spectro. (see also Hall D GLUEX)

• Strategy:
  • High Intensity electron Beam
    • Tag quasi-real photons
  • Large Acceptance Magnetic Spectrometer
  • Many final states
  • Linearly polarised photons
  • Amplitude analysis sensitive to small contributions
    • Close interplay of exp - theory
Light Quark Meson Spectroscopy

S = S₁ + S₂  J = L + S
P = (-1)^(L+1)  C = (-1)^(L+S)

Not all the J^PC combinations are allowed:
0^+  0^-  1^+  1^-  2^+  2^-  3^+ ...

Each J^PC decomposed into nonet of degenerate states

J^PC = 0^- → (π, K, η, η')
L^- → (ρ, K*, ω, Φ)
L^+ → (b₁, K₁, h₁, h₁')
...

- Quark model explains much of the observed states
- Some states not well established or not definitively assigned
- Some additional unassigned states
- Particular ?? with 0^+ scalars

Consider light quarks: u, d, s
QCD does not forbid other compositions

Some states predicted by theory (including LatticeQCD)

Evidence for some states found experimentally (but not conclusive)

Hybrids include states of exotic Q.N.
Why Photoproduction?

Photoproduction: exotic $J^{PC}$ are more likely produced by $S=1$ probe

\[ \gamma X \]

Need spin-flip for exotic q.n

No spin-flip for exotic q.n.

Linear polarization acts like a filter to disentangle the production mechanisms

Production rate for exotics is expected comparable as for regular mesons

A. Afanasev and P. Page et al. PR A57 1998 6771

A. Szczepaniak and M. Swat PLB 516 2001 72
Jefferson Lab at 12 GeV

Enhance equipment in existing halls

Beam Power: 1MW
Beam Current: 90 µA
Max Pass energy: 2.2 GeV
Max Energy Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV
CLAS12 Detector Systems

Forward Detector
- TORUS Magnet
- Forward silicon vertex tracker
- HThresh Cerenkov Counter
- LThresh Cerenkov Counter
- Forward TOF System
- Preshower calorimeter
- E.M. Calorimeter

Central Detector
- SOLENOID magnet
- Barrel silicon tracker
- Central TOF

Additional Equipment
- Micromegas (CD)
- Neutron detector (CD)
- Forward RICH
- Forward Tagger

Enable e- detection below 5°

Ready for data Summer 2017
Detect electrons at small angle to perform quasi-real photo-production experiments.

**Calorimeter:** electron energy/momentum
- Photon energy ($\nu=E-E'$)
- Polarization $\varepsilon^2 \approx 1 + \nu^2/2EE'$
- PbWO$_4$ crystals with APD/SiPM readout

**Scintillation Hodoscope:** veto for photons
- Scintillator tiles with WLS readout

**Tracker:** electron angles, polarization plane
- MicroMegas detectors

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<th>$E_{\text{scattered}}$</th>
<th>0.5 - 4.5 GeV</th>
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<td>2.5$^\circ$ - 4.5$^\circ$</td>
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<tr>
<td>$\phi$</td>
<td>0$^\circ$ - 360$^\circ$</td>
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<tr>
<td>$\nu$</td>
<td>6.5 - 10.5 GeV</td>
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<tr>
<td>$Q^2$</td>
<td>0.01 - 0.3 GeV$^2$ ($&lt;Q^2&gt; &gt; 0.1$ GeV$^2$)</td>
</tr>
<tr>
<td>$W$</td>
<td>3.6 - 4.5 GeV</td>
</tr>
</tbody>
</table>
Benchmark Reaction

11 GeV e⁻ scattering in 5cm lH₂ target
Luminosity ~ 10^{35} cm⁻² s⁻¹

e' detected in forward tagger
→γ energy (7–10.5 GeV) and polarisation
- σₐ = 0.02–0.07 GeV

3π detected in CLAS12
- σₚ = 0.5 %, σ₆ = 1 mrad, σₜ = 3 mrad

Resolution allows good discrimination from other final states (simulation)

Neutron reconstructed by missing mass

Expected number of reconstructed events from initial low luminosity data (20 days)

80 day experiment with full luminosity
80 X more events or 10^6/10MeV
Simulated Amplitude Analysis

Search for $\pi_1(1600)$ exotic in $3\pi$ final state

Detector response capable of reconstructing signals $<1\%$

But are our amplitude analysis techniques sufficient to understand such small signals?
Recent example COMPASS : $a_1(1420)$

Total 46M 3π events,

Observation of a new narrow axial-vector meson $a_1(1420)$

Fit with Isobar model

A new state!

Possible tetraquark or molecular

Nature

0.25% of signal

http://arxiv.org/
Abs/1501.05732
Jan 2015

Figure 1: (Color online) Results of the PWA in 3π mass bins of 20 MeV/c² width (data points with statistical errors only) showing the intensity of the three waves $1^{++} 0^+ f_0(980) \pi P$ (a), $2^{++} 1^+ \rho(770) \pi D$ (b), and $4^{++} 1^+$...
On the nature of $a_1(1420)$

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2Petersburg Nuclear Physics Institute, Gatchina, Russia

The resonance-like signal with axial-vector quantum numbers $J^{PC} = 1^{++}$ at a mass of 1420 MeV and a width of 140 MeV, recently observed by the COMPASS and VES experiments in the $f_0(980)\pi$ final state and tentatively called $a_1(1420)$, is discussed. Instead of a genuine new meson, we interpret this signal as a dynamical effect due to a singularity (branching point) in the triangle diagram formed by the processes $a_1(1260) \rightarrow K^*\bar{K}$, $K^+ \rightarrow K\pi$, and $K\bar{K} \rightarrow f_0(980)$ (+ c.c.). The amplitude

In general, the large data samples available nowadays both for light and heavy hadrons allow us to revisit effects which were already discussed more than 30 years ago, but were almost forgotten since then because data were too scarce to test them. These may play an important role in our understanding of the hadron spectrum.

Scattering Theory Summer School, Indiana, June 15
Developing Amplitude Analysis

CLAS : HASPECT

MESONEX

Light Meson Decay

Joint Physics Analysis Centre

JPAC

Unitarity, Analyticity, Crossing Symmetry, Low/High Energy Constraints, Veneziano Amplitudes, Van Hove Plots...

GluEx

COMPASS

BES

Others...

In general greater overlap between different experiments and theorists
HASPECT

Part of this larger effort. Preparing for CLAS12

Implement reliable amplitudes
  Revisit techniques from earlier efforts
  Accessible to all
  Common Tools e.g. IU AMPTOOLS
Apply new techniques e.g. JPAC amplitudes
Frequent meetings and Workshops
  HASPECT weekly meetings with experimentalists and JPAC
  HASPECT weeks with guests from other projects
  ATHOS Amplitude Analysis Workshops
...

Apply/develop with existing CLAS data

\[ \gamma p \rightarrow N \pi \pi \quad \gamma p \rightarrow N K K \quad \gamma p \rightarrow N \eta \]
\[ \pi \gamma p \rightarrow N \omega \quad \gamma p \rightarrow N \pi \pi \pi \quad \gamma p \rightarrow N \eta \pi \pi \]
\[ \gamma p \rightarrow N \pi^+ \pi^- K^+ \]
\[ \gamma p \rightarrow N \phi \pi \quad \gamma p \rightarrow N \phi \eta \quad \gamma p \rightarrow N \ldots \]

Theoretical support:
A. Szczepaniak (IU/JPAC), V. Mathieu (IU),
E. Santopinto (INFN-GE), A. Vassallo (GE),
J. Ferretti (UMAS)

Experimental Analysis:
M. Battagleiri, R. deVita, A. Celentano,
S. Fegan (INFN-GE), A. Filippi (INFN-TO),
D. Glazier (Glasgow), S. Hughes (Edinburgh),
K. Hicks (OhioU), S. Lombardo (Cornell),
A. Rizzo (RomaTV), I. Stankovich (Edinburgh), L. Zana (Edinburgh)
\[ p_i = q_i + p_{\perp i} \]

\[ \sum_{i=1}^{N} q_i = 0 \]

\[ q_1 = r \sin \omega \]

\[ q_2 = r \sin (2\pi/3 + \omega) \]

\[ q_3 = r \sin (4\pi/3 + \omega) \]
Example $\gamma p \rightarrow K^+ K^- p$ at around 3GeV
Applying Veneziano to $\omega$ decay

\[ \gamma p \to p \omega \to p \pi \pi \pi \]
- Decay decouples production from genuine meson-meson interaction
- $\omega$ decay $M(\pi^+\pi^-) < 0.45$ GeV
- 3-body effects

\[ A_\lambda = \varepsilon_{\mu\nu\alpha\beta} p_+^\nu p_-^\alpha p_0^\beta \varepsilon_\lambda^\mu A(s, t, u) \]
\[ I = \sum_{\lambda, \lambda'} A_\lambda^* \rho_{\lambda'}^\lambda A_{\lambda'} = K^2 W_\rho(\theta, \phi) |A|^2 \]
\[ K^2 = stu - m^2(M^2 - m^2)^2 = |\vec{p}_u \times \vec{p}_b|^2 \]
\[ W_\rho(\theta, \phi) : \text{Spin density matrix} \]
Conclusions

The CLAS detector completed data taking in 2012

Collected high quality data on wide range of experiments

Ongoing data analysis should have high impact on our understanding of light quark baryonic states

CLAS12 will be ready for data-taking in 2017

It has the potential to supply similarly high quality data studying meson states

Currently much effort is going into developing a reliable analysis framework – involves interplay of different exp/theory collaborations

GOAL : to CLARIFY (not CONFUSE) our understanding of meson spectroscopy
A SEARCH FOR EXOTIC MESONS IN $\gamma p \rightarrow \pi^+\pi^+\pi^-n$ WITH CLAS AT JEFFERSON

Figure 5.2: Typical $2^{++}$ intensity spectra; the $2^{++}1^+D$ is on the left, and the $2^{++}1^-D$ is on the right.

Figure 5.17: Typical intensities for the exotic waves: $1^{-+}1^+P$ (left), $1^{-+}0^-P$ (middle), and $1^{-+}1^-P$ (right).

Thesis: Craig Bookwalter

No Exotics signals seen so far with CLAS
Lattice QCD calculations

Standard mesons

Exotics

Pion mass = 700 MeV


in blue: overlap with $J^{PC}=1^{-+}$ operator interpreted as $qar{q}$ in S-wave + $J^{PC}_{P_{6}C_{P}}=1^{-+}$ in P-wave

• Interpretation in term of CQM + Gluon field
• Dependence on Lattice size
• Dependence on pion mass
Veneziano Amplitudes

Dual model

\[
\sum \begin{array}{c}
\Gamma(n - \alpha_s) \Gamma(n - \alpha_t) \\
\Gamma(n + m - \alpha_s - \alpha_t)
\end{array}
\]

violation of unitarity

\[
A(s, t) = \sum_{n,m} c_{n,m} \frac{\Gamma(n - \alpha_s) \Gamma(n - \alpha_t)}{\Gamma(n + m - \alpha_s - \alpha_t)}
\]

Parameters:

- trajectory \( \alpha(s) \)
- couplings \( c_{n,m} \)

\( J/\psi, \psi' \rightarrow 3\pi \)

Can be applied to

\[
\begin{align*}
\eta & \rightarrow 3\pi \\
\eta' & \rightarrow \pi\pi\eta \\
\omega & \rightarrow 3\pi \\
\phi & \rightarrow 3\pi
\end{align*}
\]

A. Szczepaniak and M. Pennington  
hep-ph/1403.5782
Veneziano Amplitudes

Dual model with 4 particles

\[ A(s, t) = \sum_{n,m} c_{n,m} \frac{\Gamma(n - \alpha_s) \Gamma(n - \alpha_t)}{\Gamma(n + m - \alpha_s - \alpha_t)} \]

Extension to 5 particles

\[ 3F_2(a, b, c; x; y) \]

Application to

\[ \gamma p \rightarrow K^+ K^- p \]

Amplitude is a sum of narrow resonances

numerical evaluation of hypergeometric functions?
From the data to the spectrum: Partial Wave Analysis

- Parametrize the cross section in terms of partial waves
- Fit to data to extract amplitudes
- A model is needed to parametrize amplitudes: Isobar Model, Dispersion Relations, ...

**Is this adequate for current and future experiments?**

- Exotics, if exist, are tiny: how to deal with the background?
- How to go beyond the Isobar Model?
- Do the amplitudes incorporate all the necessary constraints?
- Are experimental data precise and abundant enough to constrain PWA?
Triangle Singularities and XYZ Quarkonium Peaks

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We discuss analytical properties of partial waves derived from projection of a 4-legged amplitude with crossed-channel exchanges in the kinematic region of the direct channel that corresponds to the XYZ peaks in charmonium and bottomonium. We show that in general partial waves can develop anomalous branch points in the vicinity of the direct channel physical region. In a specific case, when these branch points lie on the opposite side of the unitary cut they pinch the integration contour in a dispersion relation and if the pinch happens close to threshold, the normal threshold cusp is enhanced. We show that this effect only occurs if masses of resonances in the crossed channel are in a specific, narrow range. We estimate the size of threshold enhancements originating from these anomalous singularities in reactions where the $Z_c(3900)$ and the $Z_b(10610)$ peaks have been observed.