The HASPECT Project
HAdron SPEctroscopy CenTer(s)

M. Battaglieri
INFN -GE, Italy

Outline
♦ Hadron spectroscopy
♦ Old and new challenges
♦ A road-map for future analysis
Why hadron spectroscopy

- Quantitative understanding of quark and gluon confinement
- Revealing the nature of the mass of the hadrons
- See the QCD degrees of freedom at work
- Validate lattice-QCD predictions

<table>
<thead>
<tr>
<th>Perturbative</th>
<th>Transition</th>
<th>Non- Perturbative</th>
</tr>
</thead>
<tbody>
<tr>
<td>High energy</td>
<td>Asymptotic</td>
<td>Effective</td>
</tr>
<tr>
<td>Small distance</td>
<td>freedom</td>
<td>degrees of</td>
</tr>
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<td></td>
<td></td>
<td>freedom (models)</td>
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<tr>
<td>pQCD</td>
<td></td>
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<tr>
<td>&lt;&lt; 0.1 fm</td>
<td>0.1 – 1 fm</td>
<td>&gt; 1 fm</td>
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</tbody>
</table>

Mesons & Baryons
The light quark meson spectrum

Constituent Quark Model

• Quark-antiquark pairs with total spin \( S=0,1 \) and orbital angular momentum \( L \)

\[
S = S_1 + S_2 \\
J = L + S \\
P = (-1)^{L+1} \\
C = (-1)^{L+S}
\]

Not all the \( J^{PC} \) combinations are allowed:

\[
0^{++} \quad 0^{-} \quad 0^{+} \quad 1^{++} \quad 1^{-} \quad 1^{+} \quad 2^{++} \quad 2^{-} \quad 2^{+} \quad 2^{--} \quad 3^{++} \quad 3^{-} \quad 3^{+} \quad 3^{--} \quad \ldots
\]

• SU(3) flavor symmetry

\[\rightarrow\text{ nonet } (8 \oplus 1) \text{ of degenerate states}\]

\[
J^{PC} = 0^{++} \quad \Rightarrow \quad (\pi,K,\eta,\eta') \\
1^{-} \quad \Rightarrow \quad (\rho,K^*,\omega,\Phi) \\
1^{+} \quad \Rightarrow \quad (b_1,K_1,h_1,h_1') \\
\ldots
\]

• Great success in describing the lower mass states

• A number of predicted states is not experimentally observed and assignments are uncertain

Consider light quarks: \( u,d,s \)
The gluons and the meson spectrum

• Understanding gluonic excitations of mesons and the origin of confinement
• At high energy experimental evidence is found in jet production
• At lower energies the hadron spectrum carries information about the gluons that bind quarks
• Can we find hints of the glue in the meson spectrum?

Search for non-standard states with explicit gluonic degrees of freedom

Not-allowed $J^{PC} = 0^-, 0^{+-}, 1^{+-}, 2^{+-} \ldots$

Unambiguous experimental signature for the presence of gluonic degrees of freedom in the spectrum of mesonic states
Gluonic excitation models

**Flux tube model**
- Gluonic field confined in a tube between q and anti-q
- Linear Regge trajectories
- Hybrid mesons as transverse oscillation of the tube
- Flux-tube breaking give rise to meson decay

**Bag model**
- Quarks confined inside a cavity
- Full relativistic
- Gluonic excitation: gluonic field modes by boundary conditions

**CQM + constituent gluon**
- qq + massive transverse quasi-gluon ($J_g P_g C_g$)
- Gluon adds in relative S-wave to a qq pair is S-wave or P-wave

\[
\begin{align*}
\text{qq in S-wave +} & \quad \text{Lightest multiplet} \\
J_g P_g C_g = 1^- & \quad (0, 1, 2)^{++}, 1^- \\
\end{align*}
\]

\[
\begin{align*}
\text{qq in P-wave +} & \quad \text{Lightest multiplet} \\
J_g P_g C_g = 1^- & \quad (0, 1, 2)^{++}, 1^- \\
\end{align*}
\]

- Repulsive 3-body force selects $J_g P_g C_g = 1^{+-}$ in relative P-wave added to a qq pair is S-wave or P-wave

\[
\begin{align*}
\text{qq in S-wave +} & \quad \text{Lightest multiplet} \\
J_g P_g C_g = 1^{+-} & \quad (0, 1, 2)^{++}, 1^- \\
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\end{align*}
\]
Hybrids decay modes

- Decays can only be calculated within models:
  - $^3P_0$: $M \rightarrow q\bar{q}$ with $J^{PC}=0^{++}$

- Flux-tube model:  \( \pi b_1: \pi f_1: \pi \rho: \eta \pi: \eta' \pi \)
  \( 170: 60 :5-20:0-10:0-10 \)

- Some hints:
  - hybrids with vector qq quantum number
  - pairs of not identical mesons
  - pairs of $L=0$ mesons suppressed
  - pairs of $(L=0)(L=1)$ favored

- Lattice QCD
  - sparse results (so far)
  - width overestimates (compared to other models)

To define the experimental program we need to have reliable prediction of hybrids decay
Lattice QCD calculations

Standard mesons

Exotics

\[ \rho \]

Pion mass $= 700$ MeV

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

in blue: overlap with $J^{PC}=1^{-+}$ operator interpreted as $q\bar{q}$ in S-wave + $J_g^{P_gC_g}=1^{-+}$ in P-wave

An example of latticeQCD/models interpretation

Lightest and first-excited hybrid supermultiplet in charmonium spectrum

- Coulomb Gauge QCD predictions
- confirmed by LQCD calculations
- 201X experimental confirmation?

**CHARMONIUM HYBRIDS**

Quarks in an S-wave

\[
q\bar{q}_c \left[ ^1S_0 \right] G_{8c}^* \left[ B \right] \rightarrow 1^{-+}
\]

\[
q\bar{q}_c \left[ ^3S_1 \right] G_{8c}^* \left[ B \right] \rightarrow (0,1,2)^{+-}
\]

Quarks in a P-wave

\[
q\bar{q}_c \left[ ^1P_1 \right] G_{8c}^* \left[ B \right] \rightarrow (0,1,2)^{++}
\]

\[
q\bar{q}_c \left[ ^3P_{0,1,2} \right] G_{8c}^* \left[ B \right] \rightarrow (0,1^3,2^2,3)^{+++}
\]

\(m_\pi \sim 391\,\text{MeV}\)

08

2008

**PHYSICAL REVIEW D 78, 056003 (2008)**

Heavy quarkonium hybrids from Coulomb gauge QCD

Peng Guo and Adam P. Szczepaniak

Physics Department and Nuclear Theory Center, Indiana University, Bloomington, Indiana 47405, USA

Giuseppe Galatà, Andrea Vassallo, and Elena Santopinto

INFN, Sezione di Genova, via Dodecaneso 33, 16146 Genova, Italy

(Received 23 July 2008; published 12 September 2008)

Using the nonrelativistic reduction of Coulomb gauge QCD we compute a spectrum of the low mass hybrid mesons containing a heavy quark-antiquark pair. The gluon degrees of freedom are treated in the mean field approximation calibrated to the glueball spectrum. We discuss the role of the non-Abelian nature of the QCD Coulomb interaction in the ordering of the spin-parity levels.
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 constraint PWA?

... not every bump is a resonance and not every resonance is a bump!
Why a hadron spectroscopy analysis center?

New high statistics and precise data NEEDS and adequate analysis

A modern experiment for an old problem: the $\pi_1(1600)$
- exotic $l^{-+}$ waves in $\rho\pi$, $\eta'\pi$, $f_1\pi$
- non-resonant and resonant contributions
- A dependence of $M=1$ production

Brookhaven E852 1997

$+ P$-wave $\rho\pi$ ($\pi^-\pi^-\pi^+$)

Exotic signal

Re-analysis

$\Delta\Phi(2^{++} - 1^{-+})$

$\pi$ Pb $\rightarrow$ $\pi\pi\pi$ Pb

COMPASS 2004

Intensity / (40 MeV/c$^2$)
Why a hadron spectroscopy analysis center?

New high statistics and precise data NEEDS and adequate analysis

50M on H$_2$ vs 0.4M on Pb

New reliable analysis

- Independent t-bins PWA
- Checks of systematics (different sets of waves)
- s-binning to disentangle production mechanisms

To claim new physics, we need a widely accepted analysis framework

DATA ANALYSIS and THEORY

The HASPECT project
Meson spectroscopy with photons at JLab-12 GeV

- Determination of $J^P_C$ of meson states requires PWA
- Decay and production of exclusive reactions
- Good acceptance, energy resolution, particle identification

**Hall-D - GlueX Detector**

**GlueX Detector**

- Good hermeticity
- Uniform acceptance
- Limited resolution
- Limited pID

**Hall-B - CLAS12 Detector**

- Good resolution
- Good pID
- Reasonable hermeticity
- Un-uniform acceptance
Why a hadron spectroscopy analysis center?

Present:
- e+e-: BESIII and KLOE
- B decay: LHCb
- Belle, CLEO, BABAR

Future:
- Photoproduction at JLab:
- p p-bar at GSI: PANDA

We all need a sound analysis framework!
How to develop a strong analysis framework?

★ Implementing reliable amplitudes
  • Back to classics from 60’ and 70’
  • Check amplitudes with existing data

Prepare the framework for future experiments

★ Developing common tools and procedures:
  • Common PWA framework across different experiments (eg AmpTools)
  • Wider data access and distribution (see recent CLAS Nuclear Physics Working Group effort)
  • Plugin for amplitudes and methods to judge the quality of the fit
  • Computing: fitting procedures, GPUs, etc.

Establish shared procedures and tests to claim a discovery of new physics

★ Learning & teaching
  • Promote exchanges between experimentalists and theorists
  • Write two handbooks: “HS data analysis for dummies” and “HS theory revealed”
  • Workshops and schools to share expertise and establish common rules

Promote a two-ways communication EXP-THE

HASPECT as a possible example for the HS community
  • Stable work group in Genova + satellites
  • Weekly phone/skype meetings
  • “HASPECT weeks”
Future initiatives:
★ECT* Workshop in December
The HASPECT way: a road-map for the analysis of future experiments

★ The unprecedented statistic and data quality requires an adequate analysis
★ PWA is on the boundary between experiment and theory
★ We need to develop a strong analysis framework

🌟 Beyond Isobar-Model
  coupled-channel analysis

🌟 Analyze existing photoproduction data:
  \( \pi, \eta, \eta', \pi\pi, \pi\eta, \pi\eta', \omega \pi \ldots \)

🌟 Include baryon vertex in the amplitude description
  \( N\pi, N\eta, N\eta', N\pi\pi, N\pi\eta, N\pi\eta', N\omega\pi \ldots \)

🌟 Use Regge theory to parametrize amplitude properties:
  analyticity, unitarity, FSI

🌟 Use a combination of:
  • Regge Born with low partial wave removed
  • Explicit resonance parametrization in low waves
  • FESR to constrain parametrized waves

🌟 Exploit the high statistics and accuracy of new data set
🌟 PWA in \( s \) and \( t \) bins + polarization observables (+≠ beams)

🌟 Effective Lagrangians can be used now to provide a microscopic interpretation

Goal: compare results to LQCD predictions using model to understand the underlying physics
A first attempt ...

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

M(\pi^+\pi^-) spectrum below 1.5 GeV:

- P-wave: \( \rho \) meson
- D-wave: \( f_2(1270) \)
- S-wave: \( \sigma, f_0(980) \) and \( f_0(1320) \)

Amplitude parametrization (Dispersion relation)

Related to \( \pi\pi \) scattering matrix: phase-shift, inelasticity, S-P-D-F amplitude in 0.4 GeV < \( M_{\pi\pi} \) < 1.4 GeV

\[ \langle Y_{l\mu}(E_{\gamma}, t, M) \rangle = \frac{1}{\sqrt{4\pi}} \int d\Omega_{\pi} \frac{d\sigma}{dt dM \Omega_{\pi}} Y_{l\mu}(\Omega_{\pi}) \]

First observation of the \( f_0(980) \) in a photoproduction experiment

\[ \Delta (M_{\pi\pi} (GeV)) \]

\[ \frac{d\sigma}{dt dM_{\pi\pi}} (\mu b/GeV) \]
Work in progress

$\gamma p \rightarrow p k k$
- S.Lombardo (IU)
- Full analysis from g11 CLAS6 data set
- S-P interference in 2k system

$\gamma p \rightarrow p \pi \eta$
- A.Celentano (Genova) PhD Thesis
- Amplitudes provided by V.Mathieu (ECT*) and A.Szczepaniak (IU&JLab)
- Preliminary analysis on CLAS6 data to fix parameters
- Full projection on CLAS12 and PWA

$\gamma p \rightarrow p \pi \eta'$, $\gamma p \rightarrow p \pi \omega$, $\gamma p \rightarrow p \pi \varphi$, $\gamma p \rightarrow p \eta \varphi$, $\gamma p \rightarrow p k k \pi$, $\gamma p \rightarrow p k k \pi \pi$, $\gamma p \rightarrow p k k \omega$
- Theoretical support:
  - A.Szczepaniak, V.Mathieu, E.Santopinto (INFN-GE), A.Vassallo (GE), J.Ferretti (UMAS)
- Experimental Analysis:
  - S.Fegan (INFN-GE), A. Filippi (INFN-TO), S.Hughes (Edinburgh), S. Lewis (Glasgow),
  - S.Lombardo (IU), A.Rizzo (RomaTV), L.Zana (Edinburgh)
HASPECT: Act locally but think globally!

Global strategy:
* Creation of twin and parallel centers for both analysis and theory development
* Collaboration and exchanges: personnel, short visits, ...
* Coordination via JLab Pysics Analysis Center
* Creation of a “Hadron spectrum” working group

Common funding plans:
- European-FP7 (EU calls and local): HPH, Synergy grants
- DOE-Topical -collaboration proposals
- Helmholtz Virtual-Institutes
Conclusions

✴ Recent Lattice-QCD results renew interest in Meson Spectroscopy
✴ Models are used to understand and interpret Lattice data
✴ Comprehensive meson spectroscopy program at existent (COMPASS, BES, BELLE, LHCb) and near-future facilities (JLAB, PANDA, SUPER-BELLE, BES-IV)
✴ Expected abundant and precise data requires a solid PWA analysis framework
✴ Global effort that includes: theoretically-motivated analysis, technological solutions and learning/teaching exchange between theory and experiment
✴ Coupled channel analysis, 3-body corrections, FSI, … require a new theoretical approach
✴ HASPECT and the other twin centers (JPAC, BES, GSI, Julich) want to meet the challenge
**Tuesday, May 20**

10:00 Beginning of the meeting  
10:00- 10:30 Welcome: The HASPECT working Group (M.Battaglieri)

Morning: Theory  
10:30 - 11:00 Hadronic final state interactions from DR (M.Hoferichter)  
11:00 Coffe break  
11:30 - 12:00 Direct vs. final state resonance photoproduction - two case studies (L.Bibrzycki)  
12:00 - 12:30 Padé approximants as a simple tool to extract resonance parameters from data (P.Masjuan)  
12:30-14:30 Lunch break

Afternoon: Data analysis Tools  
14: 30 - 15:00: The CLAS12 analysis framework (D.Glazier)  
15:00 - 15:30 CMU analysis tools (B.Vernansky)  
15:30 coffe break  
16:00 - 16:30: The Edinburgh MC (L.Zana)  
16:30 - 18:00 discussion

**Wednesday, May 21**

Morning: CLAS/CLAS12 analysis  
9:30 - 10:00 Veneziano amplitude (V.Mathieu)  
10:00 - 10:30 Progress in Kpipipi channel (A.Filippi)  
10:30 - 11:00 Progress in pipi (eta) channel (A.Rizzo)  
11:00 Coffe break  
11:30 - 12:00 Progress in KKpi channel (S.Fegan)  
12: 00 - 12:30 Discussion  
12:30-14:30 Lunch break

Afternoon: experiments  
14:30 - 15:00 Meson spectroscopy studies @ PANDA (E.Fioravanti)  
15:00 - 15:30 Meson spectroscopy studies @ BaBar and BESIII (V.Santoro)  
15:30 Coffe break  
16:00 - 16:30  
16:30 - 17:00 COMPASS (B.Grube)  
17:00- 17:30 Analysis techniques for quarkonium physics at Belle (U.Tamponi)  
17:30 - 18:00 Discussion

**Thursday, May 22**

Morning: Decay  
9:30 - 10:00 Amplitude analysis overview (A.Szczepaniak)  
10:00 - 10:30 Vector and D-meson three-body decays (F.Niecknig)  
10:30 - 11:00 The eta decay (D.Schott)  
11:00 Coffe break  
11:30 - 12:00 The omega decay (A.Celentano)  
End of the meeting 12:30 Lunch

**Check the web site for the latest Agenda**

Regge phenomenology in a nut-shell

• Exploit the analytical structure of the amplitude

\[ A(s, t) = 16\pi \sum_\ell (2\ell + 1) A_\ell(t) P_\ell(z_\ell) \]

\[ A(s, t) \propto \sum_e \beta_e(t) \frac{s^{\alpha_e(t)}}{\sin \pi \alpha_e(t)} \]

• Implement crossing symmetry

\[ \pi N \rightarrow \pi N \quad (s > 0, t < 0) \]

\[ \pi \pi \rightarrow N \bar{N} \quad (s < 0, t > 0) \]

• Regge trajectories

<table>
<thead>
<tr>
<th>G^+η</th>
<th>( f )</th>
<th>0.5 + 0.9t</th>
<th>( f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0^{++} )</td>
<td>( \omega )</td>
<td>0.5 + 0.9t</td>
<td>( \tilde{f} )</td>
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<tr>
<td>( 0^{-+} )</td>
<td>( \alpha )</td>
<td>0.4 + 0.9t</td>
<td>( \tilde{\omega} )</td>
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<td>( 1^{-+} )</td>
<td>( \rho )</td>
<td>0.5 + 0.9t</td>
<td>( \tilde{\alpha} )</td>
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<td>( 1^{++} )</td>
<td>( \eta )</td>
<td>0.7(t - m_\pi^2)</td>
<td>( \tilde{\rho} )</td>
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<td>( 0^{--} )</td>
<td>( h )</td>
<td>0.7(t - m_\pi^2)</td>
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<td>( \tilde{b} )</td>
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</tbody>
</table>

• Efficient and theoretically correct way to parametrize Amplitudes
• Good agreement to total xsec, differential xsec, spin observables
• Many different reactions (probes) and channels
• Regge theory can be used to parametrize Amplitudes (resonance and BG)
Duality at work

- Resonance dual to leading reggeons
- Background due to Pomeron