The meson spectroscopy program with CLAS12 at Jefferson Laboratory

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Outline

• Hadron spectroscopy and the light-quark meson spectrum
• Hybrid exotic mesons: models, LQCD and experimental hints
• the MesonEx experiment @JLAB: meson photoproduction program
• The MesonEx apparatus and the quasi-real photoproduction
• PWA and the establishment of a common analysis framework: the HASPECT network
• Summary and conclusions
Hadron Spectroscopy and light-quark meson spectrum

Why Hadron Spectroscopy?

- Exploring the nature of matter
- Understanding of quark and gluons confinement mechanism
- Studying the QCD degrees of freedom at work
- Answering to fundamental questions about fine tuning of our universe
Explicit gluonic d.o.f. in meson spectrum: hybrid mesons

**Meson Spectrum** carries information about:

- **Gluonic contribution** to the hadron structure
- **Origin of confinement**

Search for **states** with explicit gluonic degrees of freedom

**SIGNATURE:** quantum numbers not allowed by CQM
Gluonic excitation models: Flux Tube model

Several models describe possible states with gluonic excitations

**Flux Tube model:**

QCD non-abelian theory →

- gluons may interact among each other → flux tube (Confinement)

**Standard Mesons:**

- The Flux-Tube is at the ground state

- L=0, S=0
  - π, K, η...

- L=0, S=1
  - ρ, K*

**Hybrid Mesons**

- excited flux-tube

- L=0, S=0
  - +

- L=0, S=1
  - +

**First excited state of flux tube**

- $J^{PC}=1^{-+}$ or $1^{-+}$

**Quantum Numbers:**

- Hybrid: excited flux-tube
  - $J^{PC}=0^{-+}, 1^{++}, 2^{++}$

- Standard: ground-state flux-tube
  - $J^{PC}=0^{-+}, 1^{++}, 2^{++}$

**Other models:**

- Bag Model
- CQM+constituent gluon

Flux-tube breaking gives rise to meson decay (events with high particle multiplicity)

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Hints from LQCD: exotic bound states in meson spectrum

Unquenched calculations: two light flavors + 3rd heavier quark

Good Agreement between lattice calculation and experimental data:
- Number of states
- Mass hierarchy

Predictive power to search for new states

LQCD predicts lightest hybrids and glueballs below 3 GeV

- $0^{+-}$: 2 GeV
- $1^{-+}$: 1.6 GeV

Mass range accessible by MesonEx experiment at JLAB

Pion mass = 700 MeV
Hybrid mesons: experimental hints (1/2)

$\pi_1(1400) \ J^{PC}=1^{-+}$

Latest '80 claim for hybrid: joint CERN - IHEP experiment (GAMS group)  

channel $\pi^- p \rightarrow \pi^0 \eta n \ @100 \ GeV$  
$J^L=C=+ \ P=(-1)^L$  
$S$-wave$(L=0)\rightarrow a_0(980)$  
$P$-wave$(L=1)\rightarrow$ exotic?  
$D$-wave$(L=2)\rightarrow$ tensor-$a_2(1320)$

Experiment E852@BNL

Systematic studies of the reactions:

channel $\pi^- p \rightarrow \pi^0 \eta n \ @18 \ GeV$
channel $\pi^- p \rightarrow \pi^- \eta p \ @18 \ GeV$


Confirmed by Crystal Barrel

$pp\bar{p}$ annihilation at rest

channel $np\bar{p} \rightarrow \pi^- \pi^0 \eta$
channel $pp\bar{p} \rightarrow \pi^0 \pi^0 p$


Confirmed by VES@37GeV

channel $\pi^- N \rightarrow \pi^- \eta N$


Table I: Parameters for $\pi_1(1400) \rightarrow \eta \pi$

<table>
<thead>
<tr>
<th></th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL('94)</td>
<td>1370 ± 16</td>
<td>385 ± 40</td>
</tr>
<tr>
<td>CB1400</td>
<td>1360 ± 25</td>
<td>310 ± 50</td>
</tr>
</tbody>
</table>

As a second $J^{PC}=1^{-+}$ exotic meson at mass 1.6 GeV/$c^2$ was reported decaying into $\eta \pi [2]$ and $\rho \pi [19]$ channels. Accordingly, the BNL-E852 Collaboration carried out a partial-wave analysis of the $3\pi$ system on some 250,000 events.
Hybrid mesons: experimental hints (2/2)

$\pi_1(1600) \ J^{PC}=1^{-+}$

Experiment E851@BNL: analysis of 250 000 events


channel $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p \ @100 \ GeV$

Not confirmed in a re-analysis of a higher statistical sample

Experiment COMPASS: confirmed

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

To search for Hybrid exotic states the key is:

- High Statistics
- Resolution
- Acceptance
- PID

Experiment E852@BNL

MesonEx@JLAB

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MesonEx experiment @CEBAF
Continuous Electron Beam Accelerator Facility

Electron recirculating accelerator based on Superconductive Radio-Frequency technology

- **Injector**: 45 MeV polarized electron beam
- **Two LINACS**: 25 cryomodules each $\Delta E_{\text{pass}} \sim 1.2$ GeV
- **Two Ricirculating ARCS** (5 arcs each)
- **Extracted beams** to halls A, B, C (11 GeV)
- **Extracted beam** to hall D (12 GeV)
- **Maximum Delivered Current** = 200 $\mu$A (Hall-B 200 nA)
MesonEx (CLAS12) apparatus@JLAB

First run: spring 2017

Central Detector (around target)
- Solenoid magnet - 5T
- Silicon vertex tracker (SVT)
- Central TOF (CTOF)

Forward Detector (after target)
- Torus magnet (3.6 T_{peak}-6 coils)
- HT Cherenkov Counter (HTTC)
- Drift Chamber System (DC)
- LT Cherenkov Counter (LTTC)
- Forward TOF (FTOF)
- Pre-shower Calorimeter (PCAL)
- EM calorimeter (EC)

Add-on apparatus
- Micromegas
- Neutron Detector
- Rich Detector
- Forward-tagger
  photoproduction with quasi-real photons!

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Hybrid mesons photoproduction program at MesonEx

MesonEx experiment will search for exotic $J^{PC}$ states in the 1-3GeV mass range using photoproduction reactions

**Hybrid mesons and Exotics**
- Search for hybrids looking at many different states
- Charged and neutral-rich decay modes
  - $\gamma p \rightarrow p3\pi, \gamma p \rightarrow p\eta\pi$ ...

**Scalar mesons**
- Poorly known $f_0$ and $a_0$ mesons in the mass range 1-2GeV
- Theoretical indications of unconventional configurations ($qqqq$ or $gg$)
  - $\gamma p \rightarrow p2\pi, \gamma p \rightarrow p2K$ ...

**Hybrid mesons with hidden strangeness and strangeonia**
- Intermediate mass of $s$ quarks links long to short distance QCD potential
- Good resolution and K ID required
  - $\gamma p \rightarrow p\Phi\pi, \gamma p \rightarrow p\eta\Phi, \gamma p \rightarrow p2K\pi$ ...

Complementary to meson photoproduction program of GLUEX@JLAB
Why photoproduction?

EM interaction can be calculated perturbatively with high precision (well known QED)

Scattering: one-photon exchange approximation

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

- $\pi, K$ beam: Needed a spin-flip to obtain the lowest hybrid
- $\gamma$ beam: No spin-flip needed: favorite

Expected production rate for exotics and conventional mesons is comparable

Linear polarization of the photon filters background

Diffractive production via Natural (N) parity exchange

- N: $J^P = 0^+, 1^-, 2^+, ...$

Exotic production via Unnatural (U) parity exchange

- U: $J^P = 0^-, 1^+, 2^-, ...$

Linear polarized photons can distinguish between U and N

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Photoproduction reactions in Hall-B (1/2)

CLAS era:

coherent bremsstrahlung with tagged photons

Meson spectroscopy with photons in Hall-B

The Hall-B real photon tagger

With a 12 GeV electron beam only

The Hall-B existing dipole magnet can not deflect the 11 GeV primary beam on the beam-dump

Photon beam requirement

★ Tagger (initial photon energy) is required to add 'production' information to decay

★ Linear polarization is useful to simplify the PWA and essential to isolate the nature of the t-channel exchange

★ High luminosity

- Bremsstrahlung (Hall-D)
- Low $Q^2$ electroproduction (Hall-B)

\[ E_\gamma = E_e - E'_e \]

Polarized $\gamma$ beam (Linear or circular)

Now this technique is used by GLUEX experiment in Hall-D

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Photoproduction reactions in Hall-B (2/2)

**CLAS12 era:** quasi-real photoproduction

- **e⁻ beam on target:** events with scattered e⁻ at low angles (exp. 2.5° - 4.5°)
- **low Q² γ** is exchanged: quasi-real photoproduction event

By detecting the scattered electrons we may disentangle quasi-real photoproduction events from standard electron scattering events.

**Forward Tagger apparatus:** quasi real photon spectrum:

- High energy photons: \(6.5 < E_\gamma < 10.5\) GeV
- Quasi-real photons are **linearly polarized**: Polarization \(\sim 70\%-10\%\) e⁻ beam (measured event-by-event)
- High Luminosity: Equivalent γ flux \(N_\gamma \sim 5 \times 10^8\) on 5cm LH₂ \(\rightarrow L = 10^{35}\) cm\(^{-2}\)s\(^{-1}\)

8th workshop on Chiral Dynamics - Pisa 2015
The Forward Tagger Apparatus

- Placed after target
- Detects scattered e\(^{-}\) at forward angles (2.5\(^{\circ}\)-4.4\(^{\circ}\))
- Multiparticle hadronic states detected in CLAS12 - High resolution and excellent PID

**FT-cal:** PbWO\(_4\) $\rightarrow$ e\(^{-}\) Energy ($E_{\gamma}=E_{e}-E'_{e}$)

**FT-Hodo:** Scintillator tiles veto for $\gamma$

**FT-Trck:** e\(^{-}\) angles and polarization plane
From the data to the spectrum: PWA

Partial Wave Analysis (PWA): parametrization of the cross sections via the sum of partial amplitudes

- Function of quantum numbers: J,P,C,L,I
- Dynamical functions of particle momenta
- Models needed to describe each partial wave
  - Isobar model with coupled channel
  - Dispersion relations

- Is PWA feasible in CLAS12 experiment?
- Reliability? Sensitivity to Tiny effects?
PWA feasibility with MesonEx

How and how much the **detector acceptance** and **resolution distort** the reaction mechanism?  

The feasibility of **PWA** application to MesonEx data has been studied.

- Events generated using a realistic differential cross section
- filtered through the full reconstruction chain
- fitted with a set of partial waves in bins of kinematic variables (m, t)

**benchmark reaction:**  
\[ \gamma p \rightarrow \pi^+ \pi^0 \pi^- p \]

- 8 isobar channels, S,P,D wave + exotic signal
- Clas12 acceptance projected and fitted
- The results are stable against acceptance distortions

**PWA is feasible in CLAS12**
Establishing a common analysis framework

HASPECT (HAdron SPEctroscopy CenTer)

- Large community all over the world involved in hadron spectroscopy
- Exploit information for all available reactions, compare all experimental results in different channels: a comprehensive and integrated framework is mandatory
- International network for the development of common tools, databases and computing resources

Act locally but think globally
Summary and Conclusions

• The **search of exotic hybrid and strangeness-rich mesons** keeps playing a fundamental role in our understanding of the **nature of hadrons mass and confinement mechanism**.

• Thanks to a comprehensive meson spectroscopy program, the MesonEx experiment will be a privileged observation point for hybrid mesons search.

• The MesonEx experiment will use a **high intensity, quasi-real and linearly polarized “photon beam”**, obtained by tagging electrons scattered at small angles in electro-production.

• The **excellent resolution, the 4π acceptance and the good particle ID** allow MesonEx to fully detect the high-multiplicity final states expected for exotic mesons decays.

• It is mandatory to establish a **common analysis framework** among the experimental community, supported by the theoretical one, in order to share procedures and tests **to search and claim for new physics**.
Thanks for your attention
GLUEX experiment @ JLAB

Optimized for doing amplitude analyses

- Hermeticity
- Resolution
- Particle I.D.

$E_\gamma = 6\text{-}9 \text{ GeV, } 10 \text{ MeV resolution}$

- $\gamma$ flux: $10^7\text{-}10^8 \gamma/s$
- $L \sim 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ on a 30 cm LH$_2$ target
- linear polarization: 50%-15% (collective)

Collaboration has been carrying out R&D for last 5 years

Alessandro Rizzo for the CLAS collaboration
Hybrid mesons photoproduction program at MesonEx

Study the meson spectrum in the 1-3GeV mass range to identify gluonic excitation of mesons (hybrids and other quark configuration beyond CQM)

Hybrid mesons and Exotics

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Complementary to meson photoproduction program of GLUEX@JLAB

Requirements:

- $4\pi$ detector + good PID (high multiplicity)
- High intensity 6-10 GeV photon-beam

8th workshop on Chiral Dynamics -Pisa 2015

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Partial Wave Analysis (PWA): parametrization of the cross sections via the sum of partial amplitudes

- Function of quantum numbers: J, P, C, L, I
- Dynamical functions of particle momenta
- Models needed to describe each partial wave

Reliability?
Sensitivity to Tiny effects?

Only abundant and precise experimental data can constraint the partial wave shapes