Experimental Searches for Light Exotica
Precision and Progress

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Denver, CO
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• Recent decades have lead to new renaissance in hadron spectroscopy
  • New high-intensity experiments
  • More rigorous theoretical tools
  • New avenues in understanding QCD through bound states
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  • What is the origin of confinement?
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  • Do gluonic degrees of freedom manifest themselves in the bound states that we observe?
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Searching For Hybrid Mesons

- **Wish:** Unambiguous narrow Breit-Wigner peaks in a mass spectrum
- **Reality:** Must establish resonance nature by identifying pole parameters
  - Requires high-quality data in multiple channels and rigorous models: *experimentalists and theorists working closely*
- Meson QNs
  - Allowed: \(0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, 2^{--}, \ldots\)
  - Forbidden: \(0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots\)
- Hybrid Meson QNs
  - \(0^{-+}, 0^{+-}, 1^{--+}, 1^{--}, 2^{-+}, 2^{+-}, \ldots\)
- Hybrid mesons can be found with *normal* and *exotic* quantum numbers

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

"Normal" Meson

\[(J^{PC})_g = 1^{+-}\]

"Hybrid" Meson

Hybrid–Meson mass splitting \(\sim 1.0 – 1.5 \text{ GeV}\)
Light Meson Spectrum from Lattice QCD

Meson Mass (MeV)

**Negative Parity**
- $\eta'\ (0^-)$
- $\phi\ (0^+)$
- $\omega\ (1^-)$
- $\rho\ (1^+)$
- $2^{--}$
- $3^{--}$
- $4^{--}$

**Positive Parity**
- $1^{++}$
- $2^{++}$
- $3^{++}$
- $4^{++}$
- $3^-$

**Exotic**
- $0^{++}$
- $2^{+-}$
- $1^{--}$

**Lightest Hybrids**

$J^{PC} = 0^+ 1^{--} 2^{--} 3^{--} 4^{--} 2^{++} 4^{++}$

**References**

$m_\pi = 391$ MeV

$24^3 \times 128$

Isoscalar

Isovector
Light Meson Spectrum from Lattice QCD

Exotics QN mesons are “smoking gun” for existence of hybrid mesons

Light Meson Spectrum from Lattice QCD

Most searches have been focused on the lightest $1^{--}$ hybrid, the $\pi_1$

Light Meson Spectrum from Lattice QCD

To determine hybrid meson properties, need to study full spectrum of these states.

• Search by BES for resonances in $J/\psi \to \gamma \eta' \pi^+\pi^-$ in $e^+e^-$ annihilation
  • Structure seen near $2M(p)$
  • More data suggests a richer spectrum of states

BES II: PRL 95, 262001 (2005)

$$X(1835) \quad J^{PC} = 0^-$$

58x10^6 J/ψ
Precision and Spectroscopy: BES III & $J/\psi \rightarrow \gamma \eta' \pi^+\pi^-$

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X(1835) $J^P_C = 0^-$

BES III: PRL 117, 042002 (2016)

1.1x10⁹ J/ψ

58x10⁶ J/ψ

225x10⁶ J/ψ
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Searching in $\eta\pi / \eta'\pi$ @ COMPASS

- Over 20 years of reported evidence for exotic $J^{PC}$ mesons from many experiments.
  - Mass spectra generally look similar, but interpretations differ
    - $\pi_1(1400) \rightarrow \eta\pi$
    - $\pi_1(1600) \rightarrow \eta'\pi$ and $\rho\pi$
    - $\pi_1(2015) \rightarrow f_1\pi$ and $\omega\pi\pi$
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COMPASS: PLB 740, 303 (2015)
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COMPASS: \( \pi_1 \rightarrow \eta\pi / \eta'\pi \)

Extract resonance parameters with unitary reaction model

D-wave in \( \eta\pi \)

A. Jackura et al. [JPAC and COMPASS Collaborations], PLB 779, 464 (2017)
Coupled Channel Fits in $\eta\pi$ / $\eta'\pi$ @ COMPASS

- Coupled channel analysis for P-waves and D-waves
- High precision data & theoretical advances required to describe data

**P/D-wave in $\eta\pi$ / $\eta'\pi$**

A. Rodas et al. (JPAC) [Phys. Rev. Lett. 122, 042002 (2019)]
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P/D-wave in $\eta\pi / \eta'\pi$

\[ M(\pi_1) = 1564 \pm 24 \pm 86 \text{ MeV} \]
\[ \Gamma(\pi_1) = 492 \pm 54 \pm 102 \text{ MeV} \]

See: A. Rodas @ 10:30 AM Friday

A. Rodas et al. (JPAC) [Phys. Rev. Lett. 122, 042002 (2019)]
Searching in $\pi^- \pi^+ \pi^+$ @ COMPASS

- Huge data set of $\sim 50$ M exclusive $\pi^- + p \rightarrow \pi^- \pi^+ \pi^- + p_{\text{recoil}}$ events
- Partial wave decomposition using 88 waves in bins of $t$

50M $\pi^- \pi^+ \pi^+$ events

![Graph showing $m_{3\pi}$ distribution with peaks at $a_1(1260)$, $a_2(1320)$, and $\pi_2(1670)$](a)

PRD 95, 032004 (2017)

h/t S. Wallner, HADRON 2017
Searching in $\pi^- \pi^- \pi^+$ @ COMPASS

- Exotic $1^{-+}$ partial wave fit with strong resonant and non-resonant contents.
- $\pi_1$ contribution exhibits strong t-dependence

$50M \pi^- \pi^- \pi^+$ events

$M(\pi_1) = 1600+110−60$ MeV
$\Gamma(\pi_1) = 580+100−230$ MeV

PRD 98, 92003 (2018)
Light Meson Spectrum from Lattice QCD

To determine hybrid meson properties, need to study full spectrum of these states

- **\( \pi^- \pi^+ \pi^- \) @ COMPASS: \( J^{PC} = 2^{-+} \): \( \pi_2(1670) \), \( \pi_2(1880) \), \( \pi_2(2005) \)

- Observed 3 \( \pi_2 \) states: \( \pi_2(1670) \), \( \pi_2(1880) \), \( \pi_2(2005) \)
- Are these supernumerary states? Non-resonant contributions complicate interpretation.
- Need more input from theory and experiment.
\[\pi^- \pi^+ \pi^- \atop \text{COMPASS: } J^{PC} = 1^{++}: a_1(1260), a_1(1420)\]

- Unexpected state seen in \(f_0(980)\) \(\pi\) P-wave
- Much theoretical interest
- Can be described as Breit-Wigner or anomalous triangle singularity

\[ M. \text{Mikhasenko et al., PRD 91, 094015 (2015)}\]
\[ F. \text{Aceit et al., PRD 94, 09615 (2016)}\]
Meson Photoproduction

- Extend search for hybrids in fresh, complementary production mechanism
- **Photon** couples to exchanged QN via VMD, generates mesons with wide variety of $J^{PC}$: all expected hybrids can be produced
- Little existing photoproduction data. Neutral final states at these energies are mostly unexplored
- Photon polarization provides constraints on production processes
- Detailed models for amplitude analysis needed to understand spectra
The GlueX Experiment

Large acceptance spectrometer for charged and neutral particles

- **2016:** $10 \text{ pb}^{-1}$ (~80 hours of physics-quality commissioning data)
- **2017:** $45 \text{ pb}^{-1}$ (used for most public results)
- **2018:** $\sim 150 \text{ pb}^{-1}$ GlueX Phase-I complete!
Polarization Observables at GlueX

- Measurements of linearly polarized photon observables yield key info needed for hybrid meson searches
- Beam asymmetries
  - $\gamma p \rightarrow p \pi^0$
  - $\gamma p \rightarrow p \eta$
  - $\gamma p \rightarrow p \eta'$
  - $\gamma p \rightarrow \Delta^{++} \pi^-$
  - $\gamma p \rightarrow \Sigma^0 K^+$
- Spin-density Matrix Elements
  - $\gamma p \rightarrow p \rho^0$
  - $\gamma p \rightarrow p \omega$
  - $\gamma p \rightarrow p \phi$
  - $\gamma p \rightarrow \Lambda(1520) K^+$

- $\pi^0/\eta$: PRC 95, 042201 (2017)
- $\gamma p \rightarrow p \eta/\eta'$
- $\gamma p \rightarrow \Delta^{++} \pi^-$
- $\gamma p \rightarrow \Sigma^0 K^+$

Natural exchange favored (e.g. $\sqrt{2}$, %, &)
Unnatural exchange favored (e.g. !)

Laget [5,6]
JPAC [7,8]
Donnachie [9]
Goldstein [4]

Natural exchange: favored (e.g. $\gamma p \rightarrow \eta^0, \eta^+$)
Unnatural exchange: favored (e.g. $\gamma p \rightarrow \eta^-, \eta'$)
Spectroscopy Prospects @ GlueX: $\gamma p \rightarrow p + \pi\eta$

- $\pi\eta / \pi\eta'$ promising channels for early hybrid searches
- With 20% of GlueX-I data, we see several well-known mesons
- Statistics are competitive with previous experiments

$\pi^0\eta$ mass

\[ a_0(980) \quad \gamma p \rightarrow p + \pi^0\eta, \eta \rightarrow \gamma\gamma \]

\[ \eta\pi^0 \quad \pi^0\pi^0 \quad (\eta\pi^0) \]

$\pi^- p \rightarrow \eta\pi^0 n$

Counts / 10 MeV

\[ a_2(1320) \]

$M(\pi^0\eta)$ (GeV/c$^2$)

\[ a_0 \quad a_2 \]

$E852$

$\text{PLB 657 (2007) 27}$
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$\gamma \ p \rightarrow p + \pi^0 \eta, \ \eta \rightarrow \gamma \gamma$

$\gamma \ p \rightarrow \Delta^{++} + \pi^- \eta, \ \eta \rightarrow \gamma \gamma$

$\pi^0 \eta$ mass
Light Meson Spectrum from Lattice QCD

\[ J^{PC} = \begin{cases} 0^- \quad 1^- \\ 1^+ \quad 1^+ \\ 2^+ \quad 2^+ \\
\end{cases} \]

Need to establish patterns of decays for up/down and strange quark states

To study hybrids containing **strange quarks**, need clean identification of charged pions and kaons

- New addition: **DIRC** (Detection of Internally Reflected Cherenkov light)
- Installation & commissioning currently underway
Summary

- New vistas have opened up in meson spectroscopy due to availability of large, high-quality data sets
- Close collaboration between experimentalists and theorists **essential** to map these spectra
- Identification of hybrid mesons opens the door to establishing contribution of **gluonic excitations** to meson spectrum
  - $\pi_1(1600)$ pole positions determined from COMPASS data
  - Need to map out spectra in complementary production mechanisms
  - **Photoproduction** provides powerful tool to establish the full spectrum of hybrid mesons
- Expect contributions from many new experiments
  - Current: GlueX ($\gamma$), CLAS12 ($\gamma/e^-$), BES-III ($e^+e^-$), …
  - Upcoming: Belle-II ($e^+e^-$), PANDA ($p\bar{p}$), ?

See JPAC sessions Friday morning
Backup Slides
• Photon beam generated via coherent bremsstrahlung off thin diamond radiator

• Photon energies tagged by scattered electrons
  • Energy measurement precision $< 25$ MeV
  • Photon linear polarization $P_\gamma \sim 40\%$ in peak
  • Intensity of $\sim 1-5 \times 10^7 \gamma/s$ in peak
• Detailed understanding of light-quark meson spectrum requires amplitude analysis.

Collect Data
Searching for Exotics in Photoproduction

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

1. Collect Data
2. Understand production mechanisms
Searching for Exotics in Photoproduction

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

Collect Data

Understand production mechanisms

Measure cross sections
Searching for Exotics in Photoproduction

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

Collect Data ➔ Understand production mechanisms ➔ Measure cross sections ➔ Identify known mesons ➔ Search for exotics

Amplitude Analysis
Searching for Exotics in Photoproduction

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

- Collect Data
- Understand production mechanisms
- Measure cross sections
- Identify known mesons
- Search for exotics

Theoretical Models (JPAC, ....)

Amplitude Analysis
Searching for Exotics in Photoproduction

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

Collect Data

- Understand production mechanisms

Opportunistic measurements & New Ideas

Measure cross sections

- Identify known mesons

Current Efforts

- Search for exotics

Theoretical Models (JPAC, ....)

Amplitude Analysis
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0 / \eta$

- Understanding production mechanisms necessary to determine $J^{PC}$ of mesons in amplitude analyses, look at simplest reactions first
- Beam asymmetry $\Sigma$ yields information on production mechanisms
- Combining data taken with different beam polarization cancels most acceptance effects

$$\Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$$

**Exchange $J^{PC}$**

- $1^{--} : \omega, \rho$
- $1^{+-} : b, h$

JPAC: Mathieu et al., PRD 92, 074013
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0/\eta$

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$$\sigma = \sigma_0 \left[ 1 - P_{\gamma} \Sigma \cos 2(\phi_p - \phi_{\text{lin}}) \right]$$
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0 / \eta$

- Understanding production mechanisms necessary to determine $J^{PC}$ of mesons in amplitude analyses, look at simplest reactions first
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\[
\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p
\]
 Beam Asymmetries: $\gamma p \rightarrow p + \pi^0/\eta$

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Measure with $\gamma e^- \rightarrow e^- e^+ e^-$

$$
\frac{Y_\perp - F_R Y_\|}{Y_\perp + F_R Y_\|} = P_\gamma \Sigma \cos 2\phi_P
$$

Isolate $\Sigma$
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0/\eta$

- First step towards study of photoproduction amplitudes made using 2016 data
- $\Sigma \approx 1$ indicates vector exchange dominates at this energy
- First $\eta$ measurement at this energy
- Constrains background to baryon resonance production at lower energies [e.g. arXiv:1708.07779]

Beam Asymmetries: $\gamma p \rightarrow p + \eta / \eta'$

- Initial studies of $\eta$ and $\eta'$ beam asymmetries using 2017 data and additional decay modes
  - Expect similar mechanism for exotics
- Production is consistent with vector exchange dominance
  - Full GlueX-I data will provide a factor 5 more events
- Program of production amplitude studies is well underway

Statistical uncertainties only
Beam Asymmetries: $\gamma p \rightarrow \pi^- \Delta^{++}$

- Charged pseudoscalar beam asymmetry has more complicated $t$-dependence
- Preliminary results use order of magnitude more data than previous measurements

\[\chi = \pi, \rho, a_2\]

\[B.G \ Yu \ (Korea \ Aerospace \ U.), \ arxiv:1611.09629v5 \ (16 \ GeV)\]
\[J. \ Nys \ (JPAC), \ arxiv: \ 1710.09394v1 \ (8.5 \ GeV)\]

**SLAC** (16 GeV)

**GLUEX**

\[\gamma p \rightarrow \pi^- \Delta^{++} \]
\[\sim (8.5 \ GeV)\]

\[\pm 7\% \ norm. \ uncertainty\]

**Phys. Rev. D 20, 1553 (1979)**
Spin Density Matrix Elements (SDMEs): $\gamma p \rightarrow p + \omega$

- SDMEs measure the transfer of polarization from the photon to the vector meson.
- Two matrix elements are particularly sensitive to exchange particle in $\omega$ polarization transfer:
  - Pomeron: $+1/2$ and $-1/2$
  - Pion: $-1/2$ and $+1/2$
- We observe around $+0.35$ and $-0.35$
- Updating with full GlueX-I data
- $\gamma p \rightarrow p + \phi$ and $p + \rho$ also under analysis
Light Meson Spectrum from Lattice QCD

Spectroscopy Prospects: $\gamma p \rightarrow p + \pi^+ \pi^-$

- Take fresh look at $\pi^+ \pi^-$ photoproduction
  - Using two-orders of magnitude more data than SLAC
  - Enhancements seen with $M > 1$ GeV
  - Moment / amplitude analysis underway
- $K^+ K^-$ photoproduction also being studied
GlueX Detector, October 2014 (w/ Curtis Meyer, Spokesman)
The GlueX experiment is located in Hall D, newly constructed as part of the Jefferson Lab 12 GeV upgrade.

- Large acceptance solenoidal spectrometer
- Linearly polarized photon beam peaking at 9 GeV
- Detects all decay products from full hadronic photoproduction rate
- 100+ Collaborators from 26 institutions