Light Meson Spectroscopy: The GlueX Experiment

Probing the Electromagnetic Structure of Hadrons: PrimEx-\(\eta\) and CPP

Strange Hadron Spectroscopy with Secondary \(K_L\) Beam
Light Meson Spectroscopy

- Study of $q\bar{q}$ system: equivalent to the hydrogen atom
- Many broad and overlapping states in mass spectrum
Light Meson Spectroscopy

- Study of $q\bar{q}$ system: equivalent to the hydrogen atom
- Many broad and overlapping states in mass spectrum
- Characterize states by quantum numbers
- Disentangle states with angular distribution of decay

**Meson Spectroscopy**

- Total angular momentum $J$:
  $\vec{J} = \vec{L} + \vec{S}$
- Parity $P$:
  $P = (-1)^{L+1}$
- Charge conjugation $C$:
  $C = (-1)^{L+S}$

Allowed $J^{PC}$ for $q\bar{q}$ mesons: $0^{++}$, $0^{--}$, $1^{--}$, $1^{+-}$, $2^{++}$, ...
**Light Meson Spectroscopy**

Meson Spectroscopy

- Study of $q\bar{q}$ system: equivalent to the hydrogen atom
- Many broad and overlapping states in mass spectrum
- Characterize states by quantum numbers
- Disentangle states with angular distribution of decay
- Use interference to look for small signals

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Experimental Status

Evidence for Exotic States

- Forbidden $J^{PC}$ for $q\bar{q}$ mesons: $0^{+-}$, $1^{--}$, $2^{+-}$, ...
- Smoking gun for states beyond the quark-antiquark model
- Lowest mass state with $J^{PC} = 1^{-+} : \pi_1$
- Existence and interpretation still debated
Experimental Status

Evidence for Exotic States

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- Smoking gun for states beyond the quark-antiquark model
- Lowest mass state with $J^{PC} = 1^{+-}$: $\pi_1(1600)$
- Significant progress in recent years, isospin-partner $\eta_1(1855)$?

PRL 122, 042002 (2019)
The GlueX Experiment

Gluonic Excitation Experiment
GlueX at Jefferson Lab

- 12 GeV electron beam from CEBAF accelerator
- Coherent Bremsstrahlung on diamond radiator
- Linear polarization in peak $P_\gamma \sim 40\%$
- Energy tagged by scattered electrons
- Beam intensity: $1 \sim 5 \times 10^7 \gamma / s$ in peak

![Diagram of GlueX at Jefferson Lab](image)

### Polarization

![Graph showing polarization vs. energy](image)

- PARA (0°)
- PERP (90°)
- PARA (-45°)
- PERP (45°)

1.5% Systematic Uncertainty

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A. Austregesilo (aaustreg@jlab.org) — Meson Spectroscopy with GlueX
Complementary Production Mechanism

- **Wide variety of states** in spectrum accessible
- **Linear polarization** of photon provides constraints on produced system
- Understanding of **production mechanism** is prerequisite for interpretation
- Very limited photoproduction data existing at these energies
**GlueX Detector**

**Light quark meson spectroscopy**

with **nearly complete coverage**

<table>
<thead>
<tr>
<th>Timeline</th>
<th>$\int \mathcal{L}$ (pb$^{-1}$)</th>
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<tr>
<td>2017</td>
<td>22</td>
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<tr>
<td>2018</td>
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<tr>
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</tr>
</tbody>
</table>

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A. Austregesilo (aaustreg@jlab.org) — Meson Spectroscopy with GlueX
GlueX + Theory

- High statistical precision requires robust theoretical models and capable analysis frameworks
- Collaboration: experiment and theory working together on analysis and interpretation
Polarization Transfer
First GlueX Publication: PRC 95, 042201 (2017)

$\pi^0$ and $\eta$ from 2016 Commissioning Data

- Modeling production mechanism: $\Sigma$ sensitive to exchanged $J^{PC}$
- Cancel systematic effects by rotating polarization plane by $90^\circ$
- First measurement for $\eta$ in this energy

\[
\sigma_{\text{pol}}(\phi) = \sigma_{\text{unpol}} \left[ 1 - P_\gamma \Sigma \cos 2\phi \right]
\]
Pseudoscalar Meson Photoproduction

Beam Asymmetry Measurements
- \( \eta \): significantly higher precision
- \( \eta' \): first measurement in this energy
- \( \pi^- \): unnatural exchange important at small \(-t\)
- \( K^+ \): no visible \( t \)-dependence

Photoproduction
- Neutral exchange: natural parity exchange dominates
- Charge exchange: unnatural parity exchange for small \( t \)
Full angular distribution of vector meson production and decay is described by spin-density matrix elements $\rho_{ij}^k$.

Linear beam polarization provides access to nine linearly independent SDMEs.

Intensity $W$ is expressed as function of angles $\cos \vartheta, \varphi, \Phi$ and degree of polarization $P_\gamma$.

\[
W(\cos \vartheta, \varphi, \Phi) = W^0(\cos \vartheta, \varphi) - P_\gamma \cos(2\Phi) W^1(\cos \vartheta, \varphi) - P_\gamma \sin(2\Phi) W^2(\cos \vartheta, \varphi)
\]

\[
W^0(\cos \vartheta, \varphi) = \frac{3}{4\pi} \left( \frac{1}{2} (1 - \rho_{00}^0) + \frac{1}{2} (3 \rho_{00}^0 - 1) \cos^2 \varphi - \sqrt{2} \text{Re} \rho_{10}^0 \sin 2\varphi \cos \varphi - \rho_{1-1}^0 \sin^2 \varphi \cos 2\varphi \right)
\]

\[
W^1(\cos \vartheta, \varphi) = \frac{3}{4\pi} \left( \rho_{11}^1 \sin^2 \varphi + \rho_{00}^1 \cos^2 \varphi - \sqrt{2} \text{Re} \rho_{10}^1 \sin 2\varphi \cos \varphi - \rho_{1-1}^1 \sin^2 \varphi \cos 2\varphi \right)
\]

\[
W^2(\cos \vartheta, \varphi) = \frac{3}{4\pi} \left( \sqrt{2} \text{Im} \rho_{10}^2 \sin 2\varphi \sin \varphi + \text{Im} \rho_{1-1}^2 \sin^2 \varphi \sin 2\varphi \right)
\]

$t$-dependence of SDMEs

$\gamma p \rightarrow \rho(770)p$

- High precision with only fraction of data set
- Uncertainties dominated by systematics
- Agree with model up to $-t \approx 0.5 \text{ GeV}^2/c^2$

[ PRD 97 094003 (2018) ]
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  [ PRD 97 094003 (2018) ]
- Detailed studies of mass and energy dependence will follow

Other Channels...

- Analysis of $\omega(782), \phi(1020)$ ongoing
- Natural-parity exchange generally dominates
- Improve theoretical description of photoproduction process
- Understand and evaluate detector acceptance
Cross Section Measurements

\[ \eta \text{ Diff. Cross Sec. } 8.0 < E_\gamma < 8.5 \text{ GeV} \]

\[ \frac{d\sigma}{dt} \text{ (nb/GeV}^2\text{)} \]

- J.M. Laget
- JPAC
- EtaMAID 2018
- Handbag (Kroll & Passek-Kumerick)
- GlueX-I Prelim. Results

\[ \gamma p \rightarrow \eta p \]
- \( t \)-channel dominant, but coverage of entire kinematic regime
- Regge models at low \(|t|\), Handbag for intermediate \(|t|\)

Energy coverage: 3 to 12 GeV

Overlap with previous measurements

Other Channels...

Precise measurement for many different final states ongoing

Consistency between decay modes limits systematic uncertainties
Cross Section Measurements

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- $t$-channel dominant, but coverage of entire kinematic regime
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The $\eta(')\pi$ Systems

M. Albrecht [Tuesday, Exotic Hadrons]

- Strongest evidence for exotic $\pi_1(1600)$ from COMPASS in this channel
- Competitive statistical precision, but different production and multiple decay modes
- Collaboration with theory on development of amplitudes and models

- Clear signals for $a_0(980)$ and $a_2(1320)$
- Different angular distribution between charged (top) and neutral (bottom) final state
- Production mechanism populates states with different spin-projections

⇒ Amplitude Analysis
New amplitude formalism with $Z^m_\ell(\Omega, \Phi) = Y^m_\ell(\Omega)e^{-i\Phi}$:

$$I(\Omega, \Phi) \propto (1 - P_\gamma) \left| \sum_{\ell, m}[T]^{(-)}_m \text{Re}Z^m_\ell(\Omega, \Phi) \right|^2 + (1 - P_\gamma) \left| \sum_{\ell, m}[T]^{(+)}_m \text{Im}Z^m_\ell(\Omega, \Phi) \right|^2 +$$

$$+(1 + P_\gamma) \left| \sum_{\ell, m}[T]^{(+)}_m \text{Re}Z^m_\ell(\Omega, \Phi) \right|^2 + (1 + P_\gamma) \left| \sum_{\ell, m}[T]^{(-)}_m \text{Im}Z^m_\ell(\Omega, \Phi) \right|^2$$

Describes all two-pseudoscalar meson systems ($\pi\pi$, $KK$, $\pi\eta$, etc.), extension to vector-pseudoscalar systems → A. Schertz [this Session, 10:35am]

Fully mass-independent analysis difficult due to complexity of wave set: $S^\pm_0, P^\pm_{-1,0,1}, D^\pm_{-2,-1,0,1,2}, \ldots$

 Require theory input to limit amplitudes (TMD model) or constrain mass dependence of known resonances
Semi-Massdependent Method: Impose Breit-Wigner Shape for $a_2(1320)$

- Good agreement with theory prediction, demonstrate validity of method
- Separation of natural and unnatural parity exchange mechanisms
- $a_2(1320)$ signal as reference wave for exotic $\pi_1(1600)$ in $\eta'\pi$
Projection for $\pi_1(1600) \rightarrow \eta^{(')}\pi$

- Upper limits for $\pi_1(1600)$ branching fractions from LQCD

- Projections combine LQCD with measured $a_2(1320)$ and (iso-vector) $b_1\pi$ cross sections
Projection for $\pi_1(1600) \rightarrow \eta^{(')}\pi$

- Upper limits for $\pi_1(1600)$ branching fractions from LQCD
- Saturate measured $\omega\pi\pi$ cross section ($I = 1$)

- Projections combine LQCD with measured $a_2(1320)$ and (iso-vector) $b_1\pi$ cross sections
- Expect small signal in $\eta\pi$, but signal could saturate $\eta^{(')}\pi$ channels → enforced effort
The Future of GlueX

Detector Upgrades

- DIRC: Extend kaon/pion separation, fully commissioned in Fall 2019
- FCal2: PbWO$_4$ insert with higher granularity, will be completed in 2024

GlueX Phase II + JLab Eta Factory

- Started 2020, 2023, continue with FCal2 in 2024
- Emphasis on final states with strangeness
- Higher luminosity: rare $\eta$ decays

→ S. Schadmand [Tuesday, New Facilities]
PrimEx-$\eta$: Precision measurement of $\eta$ decay

- Primakoff production of $\eta$ meson on nuclear target (Helium)
- Precise measurement of $\eta \rightarrow \gamma \gamma$ decay width
- Determine fundamental properties: light quark mass ratio, $\eta - \eta'$ mixing angle
- Experiment completed in three beam times 2019, 2021 and 2022

→ L. Gan [Thursday, BSM]
\(\pi^\pm\) and \(\pi^0\) Polarizability

\[
\vec{p} = -\alpha \vec{E}
\]

\[
E \approx 10^{23} \text{V/m}
\]

\[
\alpha \approx 10^{-4} \text{fm}^3
\]

Status and Projection for Sensitivity

- Fundamental property of the strong interaction, precise predictions from \(\chi^\text{PT}\)
- Primakoff production of \(\pi^+\pi^-\) and \(\pi^0\pi^0\) with 6 GeV polarized photon beam on Pb target
- New wire chambers behind forward calorimeter to detect muon background, data recorded in 2022
\( \pi^\pm \) and \( \pi^0 \) Polarizability

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- New wire chambers behind forward calorimeter to detect muon background, data recorded in 2022
- Precision for \( \pi^\pm \) estimated to be comparable with COMPASS, but complementary systematic effects
- Neutral pion polarizability has never been measured
Strange Hadron Spectroscopy with Secondary $K_L$ Beam

- Use photon beam to produce beam of neutral Kaons, sweep away charged tracks
- World-wide unique facility combined with versatile GlueX detector, planned to be ready in 2026
- Hyperon spectroscopy to identify missing baryon resonances
- $K\pi$ scattering to study $\kappa$ meson
Summary

Status of the GlueX Experiment

- Full data set for initial phase of GlueX **available** and under **active analysis**
- Several exciting **physics results**, many more to come
- GlueX Phase II in process: focus on meson spectrum with **strangeness** content
Summary

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Beyond GlueX

- Light meson spectroscopy is active field of research with global effort
- Versatile GlueX detector used for precision measurements of QCD
- Detector upgrades for more science potential
- Development of new programs:
  → P. Rossi “New opportunities with Jefferson Lab at 22 GeV” [Thursday, Plenary]
## Status of the GlueX Experiment

- Full data set for initial phase of GlueX **available** and under **active analysis**
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## Beyond GlueX

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GlueX gratefully acknowledges the support of several funding agencies and computing facilities:

| gluex.org/thanks |
E. Chudakov
“J/ψ photoproduction close to threshold at GlueX”
Monday June 5, 3:12pm, 5H (Hadron decays, production and interaction)

M. Albrecht
“Search for Exotic Hadrons in η(())π at GlueX”
Tuesday June 6, 4:30pm, 4H (Exotic hadrons and candidates)

S. Schadmand
“Precision tests of fundamental physics with light meson decays”
Tuesday June 6, 5:40pm, 1B (New facilities)

F. Nerling
“Measurement of the photoproduction cross section for γp → φπ⁺π⁻p and search for the Y(2175) at GlueX”
Tuesday June 6, 5:00pm, 4H (Exotic hadrons and candidates)

A. Schertz
“Vector-Pseudoscalar Partial Wave Analysis at GlueX”
Friday June 9, 10:35am, 5L (Light meson spectroscopy)
Amplitude Analysis

Step 1: Mass-Independent Partial-Wave Analysis

- Partial wave $\psi_w(\tau)$: Complex-valued amplitude which describes angular distribution of decay products
- Constant in a narrow mass bin: model-independent
- Total intensity distribution $I$ in each mass bin: coherent sum of amplitudes with production coefficients $T_w$

$$I(\tau) = \left| \sum_w T_w \psi_w(\tau) \right|^2$$
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Step 2: Model for Mass Dependence for Results from Step 1
- Breit-Wigner function for narrow, isolated resonances
- Approximations for coupled channels: Flatté, K-matrix, ...
- Amplitudes for dynamical effects: triangle singularity, ...
- Treatment of background

Extraction of physical quantities: pole positions, coupling constants
Threshold for $J/\psi$ production: $E_\gamma = 8.22$ GeV

- Electron identification: $E/p$ in calorimeters, pion background suppression by $10^{-4}$
- Kinematic Fit with 0.1% precision on photon beam energy
$J/\psi$ Photoproduction at Threshold

$\gamma p \rightarrow J/\psi p$, $J/\psi \rightarrow e^+ e^-$

Threshold for $J/\psi$ production: $E_\gamma = 8.22$ GeV

- Electron identification: $E/p$ in calorimeters, pion background suppression by $10^{-4}$
- Kinematic Fit with 0.1% precision on photon beam energy
- Cross section normalized by non-resonant $e^+ e^-$ production (Bethe-Heitler)
Energy dependence probes

- Production dynamics
  Brodsky et al. [PRL 498 (2001)]
- Gluon distribution in proton
  Kharzeev et al. [NPA 661, 568 (1999)]
**Energy dependence probes**

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  Brodsky et al. [PRL 498 (2001)]
- Gluon distribution in proton
  Kharzeev et al. [NPA 661, 568 (1999)]

**Search for Resonance in J/ψp**

- No evidence for $P^+_c$ states
- Upper limit for $J^{PC} = 3/2^-$ states
  
<table>
<thead>
<tr>
<th>State</th>
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<tbody>
<tr>
<td>$P^+_c(4312)3/2^-$</td>
<td>&lt; 2.9%</td>
</tr>
<tr>
<td>$P^+_c(4440)3/2^-$</td>
<td>&lt; 1.6%</td>
</tr>
<tr>
<td>$P^+_c(4457)3/2^-$</td>
<td>&lt; 2.7%</td>
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</table>

- Disfavors hadrocharmonium and some molecular models

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**Cross Section at Threshold**

PRL 123, 072001 (2019)

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LHCb, PRL 122, 222001 (2019)  
JPAC, PRD 94, 034002 (2016)
4 times more data, smaller systematic uncertainties, precise measurement of $d\sigma/dt$

Results relevant for fundamental properties: proton mass, gravitational form factors, scattering length
4 times more data, smaller systematic uncertainties, precise measurement of \( \frac{d\sigma}{dt} \)

Results relevant for fundamental properties: proton mass, gravitational form factors, scattering length

Possible evidence for contribution from open charm production