Hadron Spectroscopy at GlueX

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Outline





Strong-Coupling QCD The GlueX Experiment

Outline





Strong-Coupling QCD The GlueX Experiment

Non-Perturbative QCD



How does QCD give rise to excited hadrons?

- What is the origin of confinement?
- e How are confinement and chiral symmetry breaking connected?
- What role do gluonic excitations play in the spectroscopy of light mesons, and can they help explain quark confinement?

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Answers to these questions will not be the direct result of some experiments.

- Models need to link observables to these fundamental questions.
- Significant observables:
 - Excitation spectra and electromagnetic couplings
 - Response of hadronic properties to a dense nuclear environment

Strong-Coupling QCD The GlueX Experiment

Non-Perturbative QCD



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Strong-Coupling QCD The GlueX Experiment

GlueX Core Mission: Search for Hybrid Mesons

Quantum Numbers $J^{PC} \equiv {}^{2S+1}L_J$

- Parity: $P = (-1)^{L+1}$
- Charge Conjugation: C = (-1)^{L+S} (defined for neutral mesons)
- **G** parity: $G = C(-1)^{l}$

$$\frac{L = 0, \ S = 0}{\text{e.g. } \pi, \ \eta \ (J^{PC} = 0^{-+})}$$

$$\frac{L = 0, \ S = 1:}{\text{e.g. } \rho, \omega, \phi (J^{PC} = 1^{--})}$$

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12 GeV CEBAF upgrade has high priority (DOE Office of Science, Long Range Plan) "[key area] is experimental verification of the powerful force fields (*flux tubes*) believed to be responsible for quark confinement."

Forbidden States (Exotics): $J^{PC} = 0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, \cdots$ (hybrid kaons do not have exotic QNs)

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Meson Spectroscopy on the Lattice



J. J. Dudek et al., PRD 84, 074023 (2011)

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Strong-Coupling QCD The GlueX Experiment



The GlueX Collaboration

- \sim 135 members, 29 institutions (Armenia, Canada, Chile, China, Germany, Greece, Russia, UK, USA)
- GlueX phase-I complete (120 PAC days)
- First physics published in 2017



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The GlueX Experiment: Photon Beamline



Strong-Coupling QCD The GlueX Experiment

Spectroscopy and Amplitude Analysis

Courtesy of Sean Dobbs Amplitude Experiment **Analysis** Search for Exotics Opportunistic Polarization Theoretical Measurements Transfer Models & New Ideas Understand Identify Photoproduction Known **Mechanisms** Mesons Spin-density Measure Matrix Elements Cross sections

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Strong-Coupling QCD The GlueX Experiment

Spectroscopy and Amplitude Analysis

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Beam Asymmetries Spin-Density Matrix Elements Spectroscopy of Ξ Resonances

Outline

Introduction and Motivation
 Strong-Coupling QCD

• The GlueX Experiment

Padron Spectroscopy at GlueX

- Beam Asymmetries
- Spin-Density Matrix Elements
- Spectroscopy of Ξ Resonances

Summary and Conclusions



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Beam Asymmetries Spin-Density Matrix Elements Spectroscopy of \equiv Resonances

Measurement of Beam Asymmetries: $\gamma \rho \rightarrow \rho \pi^0$

Beam Asymmetry, Σ , yields information on production mechanism:



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

V. Mathieu et al., Phys. Rev. D 92, no. 7, 074004 (2015)

Experimentally:

$$\frac{Y_{\perp} - F_R Y_{\parallel}}{Y_{\perp} + F_R Y_{\parallel}} = P_{\gamma} \Sigma \cos 2\phi_{\rho}$$



Measurement of Beam Asymmetries: $\gamma p \rightarrow p \pi^0 / \eta$



H. Al Ghoul et al., Phys. Rev. C 95, no. 4, 042201 (2017)

Significantly improved data quality

- First measurement of the η beam asymmetry for 8.4 < E_γ < 9.0 GeV.
- $\bullet~$ Beam asymmetries close to unity: $\Sigma\approx 1$
 - → Dominance of vector-meson exchange No dip around $-t = 0.5 \text{ GeV}^2$ for π^0
- Comparison with Regge calculations contributes to understanding of production mechanisms in photoproduction.
 - → Step toward search for exotic mesons.

Measurement of Beam Asymmetries: $\gamma p \rightarrow p \eta / \eta'$



S. Adhikari et al., Phys. Rev. C 100, no.5, 052201 (2019)

Significantly improved data quality

- First measurement of the (η)/η' beam asymmetries for 8.2 < E_γ < 8.8 GeV.
- Beam asymmetry close to unity: $\Sigma_\eta \approx 1$
 - → Dominance of vector-meson exchange No indication for 2⁻⁻ exchange
- Comparison with Regge calculations contributes to understanding of production mechanisms in photoproduction.
 - → Step toward search for exotic mesons.

Beam Asymmetries Spin-Density Matrix Elements Spectroscopy of \equiv Resonances

Measurement of Beam Asymmetries: $\gamma p \rightarrow \Delta^{++} \pi^{-}$

- S. Adhikari *et al.*, Phys. Rev. C **103**, no. 2, L022201 (2021) F. Afzal *et al.*, Physics Letters B **863**, 139368 (2025)
- Charge exchange process
- Dominated by π exchange at low |t|



I |t| < 0.45 (GeV/c)²

- Σ negative
- neg. naturality π exchanged favored

2 $|t| < 0.25 \, (\text{GeV}/c)^2$

- $\boldsymbol{\Sigma}$ negative, downward sloped
- mixed naturality modifications to one-π exchange

I |t| > 0.45 (GeV/c)²

- Σ positive
- positive naturality vector ρ and tensor a₂ exchange

Beam Asymmetries Spin-Density Matrix Elements Spectroscopy of \equiv Resonances

Measurement of Beam Asymmetries

[GlueX] Phys. Rev. C **103**, no. 2, L022201 (2021) [GlueX] Physics Letters B **863**, 139368 (2025)

- Charge exchange process
- Dominated by π exchange at low |t|





Phys. Rev. C 101, no. 6, 065206 (2020)

- Consistent with unity
 - → Dominant natural parity exchange

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Beam Asymmetries Spin-Density Matrix Elements Spectroscopy of \equiv Resonances

Spin-Density Matrix Elements: $\gamma p \rightarrow \Delta^{++} \pi^{-}$



[GlueX] PL B 863, 139368 (2025)

$$\rho_{ij}^{N/U} = \rho_{ij}^{0} \pm \rho_{ij}^{1}$$

$$\Sigma = \left(\rho_{11}^{N} + \rho_{33}^{N}\right) - \left(\rho_{11}^{U} + \rho_{33}^{U}\right)$$
$$= 2\left(\rho_{11}^{1} + \rho_{33}^{1}\right)$$



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Beam Asymmetries Spin-Density Matrix Elements Spectroscopy of \equiv Resonances

Spin-Density Matrix Elements: $\gamma p \rightarrow p \phi(1020)$

~~ 0.7 GLUE 0.6 Preliminary 0.5 0.4 0.3 0 0.2 0.4 0.6 0.8 1 -t (GeV²) -0° .2 0 0. 0 -0.1 GLUE Preliminar -0.20.2 0.4 0.6 0.8 1 -t (GeV²) n

[GlueX] arXiv:2504.0119 [hep-ex]

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Spin-Density Matrix Elements

Spin-Density Matrix Elements: $\gamma p \rightarrow p \phi(1020)$



[GlueX] arXiv:2504.0119 [hep-ex]

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Spin-Density Matrix Elements

Spin-Density Matrix Elements: $\gamma p \rightarrow p \phi(1020)$



[GlueX] arXiv:2504.0119 [hep-ex]

→ E > < E</p>



Small systematic deviation of P_{σ} from pure natural-parity exchange due to

Small background, or

• Small contribution from π or η , for instance.

Beam Asymmetries Spin-Density Matrix Elements Spectroscopy of E Resonances

Spectrum of *N*^{*} **Resonances**



V.C. & W. Robert	s, Rep.	Prog.	Phys.	76 (2	2013)
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N	(D,L^P_N)	S	J^P		Octet M	embers		Singlets
0	$(56, 0_0^+)$	$\frac{1}{2}$	$\frac{1}{2}^{+}$	N(939)	$\Lambda(1116)$	$\Sigma(1193)$	Ξ(1318)	-
1	$(70, 1_1^-)$	1 2 3	$\frac{1}{2}^{-}$ $\frac{3}{2}^{-}$ $\frac{1}{2}^{-}$	N(1535) N(1520) N(1650)	$\Lambda(1670)$ $\Lambda(1690)$ $\Lambda(1800)$	$\Sigma(1620)$ $\Sigma(1670)$ $\Sigma(1750)$	$\Xi(1690) \\ \Xi(1820)$	$\Lambda(1405)$ $\Lambda(1520)$
		2	$\frac{2}{3} - \frac{1}{2} - \frac{1}{2}$	N(1700) N(1675)	Λ(1830)	$\Sigma(1775)$		
2	$(56, 0_2^+)$ $(70, 0_2^+)$	$\frac{1}{2}$ $\frac{1}{2}$	$\frac{\frac{1}{2}^{+}}{\frac{1}{2}^{+}}$	N(1440) N(1710)	$\begin{array}{c} \Lambda(1600) \\ \Lambda(1810)^{\dagger} \end{array}$	$\Sigma(1660) \\ \Sigma(1770)^{\dagger}$		-
	$(56, 2^+_2)$	2 1 2	$\frac{\frac{3}{2}}{\frac{3}{2}+}$	$N(1720)^{\dagger}$ N(1680)	$Λ(1890)^{\dagger}$ $Λ(1820)^{\dagger}$	$\Sigma(1840)^{\dagger}$ $\Sigma(1915)^{\dagger}$		-
	$(70, 2_2^+)$	$\frac{1}{2}$	$\frac{\frac{2}{3}}{\frac{5}{2}}$ +	N(1860)		B (1010)		
		$\frac{3}{2}$	1+ 2+ 2+ 2+	$N(1880) \\ N(1900)^{\dagger}$		$\Sigma(2080)^{\dagger}$		-
(00.1+	(00, 1 ⁺)		$\frac{\frac{3}{2}}{\frac{7}{2}}$ + $\frac{7}{2}$ + 1+	N(2000) N(1990)	$\Lambda(2110)^{\dagger}$ $\Lambda(2020)$	$\Sigma(2070)^{\dagger}$ $\Sigma(2030)^{\dagger}$		-
	$(20, 1_2^+)$	2	$\frac{1}{2} + \frac{1}{2} + \frac{1}$	$N(2100)^{\dagger}$ $N(2040)^{\dagger}$	_	_	_	

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Hadron Spectroscopy at GlueX

Beam Asymmetries Spin-Density Matrix Elements Spectroscopy of \equiv Resonances

The Ξ^* and Ω^* Spectrum from Lattice QCD



Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

→ Counting of states of each flavor and spin consistent with QM for the lowest negative- and positive-parity bands.

Beam Asymmetries Spin-Density Matrix Elements Spectroscopy of \equiv Resonances

CLAS g11a: Excited States in $\gamma p \rightarrow K^+ K^+ \pi^- (X)$

From the paper: Although a small enhancement is observed in the $\Xi^0 \pi^-$ invariant mass spectrum near the controversial 1-star $\Xi^-(1620)$ resonance, it is not possible to determine its exact nature without a full partial wave analysis. Phys. Rev. C **76**, 025208 (2007)

Need high-statistics, high-energy data from an experiment designed to see Ξ states:

- 3- or 4-track trigger
- Reconstruction of full decay chain
- Higher photon energy
- Improved detectors

→ CLAS 12 and GlueX at Jefferson Lab



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Possible Production Mechanisms



Spectroscopy of Ξ Resonances

Summary and Open Questions

Spectroscopy of (low-mass) \equiv resonances very important to understand the systematics of the baryon spectrum:

- What about the properties of the Ξ(1620) / Ξ(1690) states?
- Is the $\Xi(1620)$ more than one state? Is the $\Xi(1620)$ the doubly strange partner of the $\Lambda(1405)$?
- Where is the radial excitation of the Ξ(1320)?



Badial Excitations (Roper-like states)

for the octet members with $J^P = \frac{1}{2}^+$

Arifi et al., PRD 105, 094006

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Summary and Conclusions

Quantum Chromodynamics (QCD) is (most likely) the correct theory of strong interactions. However, the theory remains still fairly untested and not very well understood at low energies (spectra and properties of hadrons).

Hadron spectroscopy is a powerful tool to scrutinize ideas on the effective degrees of freedom that govern hadron dynamics.

- QCD-inspired models have been very successful at describing the overall features of the spectrum of mesons and baryons, and also their decays, form factors, transition form factors, magnetic moments, etc.
- However, these models have also exhibited important failures:
 - Link between partonic degrees of freedom seen in deep inelastic scattering and constituent quarks remains poorly understood.
 - Experiments have yet to provide compelling evidence for gluonic excitations (glueballs, hybrids, etc.).

https://gluex.org/thanks.html

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Upper Limit on Photoproduced Spin-Exotic $\pi_1(1600)$



Upper Limit on Photoproduced Spin-Exotic $\pi_1(1600)$



[GlueX] PRL 133, 261903 (2024)

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Photoproduction from proton in the range (0.1 < -t < 0.5) (GeV/*c*)²

- $\sigma[\gamma p \to \pi_1^0(1600) \, p] < 206 \, \text{nb}$
- $\sigma[\gamma p \to \pi_1^-(1600) \Delta^{++}] < 577 \text{ nb}$

→ Best discovery potential to find $\pi_1(1600)$ is in its $\eta'\pi$ decay mode.

Backup Slides

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GlueX: Cross Sections in $\gamma p \rightarrow K^+ K^+ \equiv (1320)^-$



[CLAS Collaboration], Phys. Rev. C 98 (2018) 6, 062201

Measurements of

- Differential cross sections
- Polarization observables
- Mass, width, spin
- Band denotes current systematic uncertainties, not final.

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