Exploring Photoproduced $\eta^{(\prime)}\pi^0$ Systems in the Search for Exotic Hadrons at GlueX

2025 European Physical Society Conference on High Energy Physics - Marseille, France

Zachary Baldwin | July 10, 2025

Carnegie Mellon University



Office of Science

QCD and Hadronic Physics





Total angular momentum



Parity

| Allowed J ^{PC} quantum numbers | | | | | | | | | | | |
|---|---|----------|---|---|----------|---|---|----------|--|--|--|
| L | S | J^{PC} | L | S | J^{PC} | L | S | J^{PC} | | | |
| 0 | 0 | 0^{-+} | | 0 | 1+- | 2 | 0 | 2-+ | | | |
| 0 | | 1 | 1 |] | 0^{++} | 2 | | 1 | | | |
| | | | 1 | | 1++ | 2 | | 2 | | | |
| | | | 1 | 1 | 2++ | 2 | | 3 | | | |



$J = 0, 1, 2, \dots$

$$P = (-1)^{L+1}$$

Charge Conjugation $C = (-1)^{L+S}$

L is the relative orbital angular momentum of the q and \bar{q}

S is the total intrinsic spin of the $q\bar{q}$ pairs







Total angular momentum



Parity

Allowed J^{PC} quantum numbers $L S J^{PC} L S J^{PC}$ $L S J^{PC}$ $0 0^{-+} 1 0 1^{+-} 2 0 2^{-+}$ () $1 \quad 0^{++}$ 2 1 \mathbf{O} 1 1++ 2 1 2

Forbidden J^{PC} quantum numbers

$$0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$$

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Observation of any system with quantum numbers forbidden in the constituent quark model, provides direct evidence for a non- $q\bar{q}$ configuration







Total angular momentum



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JLAB-THY-11-131 TCD-MATH 11-02

Isoscalar meson spectroscopy from lattice QCD Jozef J. Dudek,^{1, 2, 1} Robert G. Edwards,¹ Bálint Joó,¹ Michael J. Peardon,³ David G. Richards,¹ and Christopher E. Thomas¹ (for the Hadron Spectrum Collaboration) had spec

(for the Hadron Spectrum Collaboration) ratory, 12000 Jefferson Avenue, Newport News, VA 23506, USA of Physics, Old Dominion University, Norfolk, VA 23529, USA of Mathematics, Trinity College, Dublin 2, Ireland

ecision an excited spectrum of single-particle isoscalar meson of high spin and, for the first time, light exotic J^{FC} isoscalars, uction has enabled us to overcome the long-standing challenge tion contributions. Hidden-flavor mixing angles are extracted be close to ideally flavor

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Support quark annihilation d source of a probability of d and d are constructed in [8, 9] (of t^{α} the techniques developed probability of t^{α} and t^{α} are an expectively and are the angles include $(t^{\alpha}, t^{\alpha}, t^{\alpha},$

Introduction: Mesons which have all flavor quantum numbers equal to zero, known as isoscalars, form a par-numbers equal to zero, known as isoscalars, form a par-numbers equal to zero, known as isoscalars, form a par-numbers equal to zero, known as isoscalars, form a par-numbers equal to zero, known as isoscalars, form a par-numbers equal to zero, known as isoscalars, form a par-numbers equal to zero, known as isoscalars, form a par-numbers equal to zero, known as isoscalars, form a par-numbers equal to zero, known as isoscalars, form a par-numbers equal to zero, known as isoscalars, form a par-numbers equal to zero, known as isoscalars, form a par-numbers equal to zero, known as isoscalars form a par-numbers and ingeneral the QCD eigenstates will be of pure glue, and in general the QCD eigenstates will be and hidden-flavor content of isoscalar mesons we can in-fer a phenomenology of annihilation dynamics in QCD. The full that many low-lying isoscalar mesons come in identifiable pairs with a strong prefer-menons of ideal flavor mixing; prominent examples include ϕ where the admixture of $|s\bar{s}\rangle$ into the dominantly ϕ where the admixture of $|s\bar{s}\rangle$ into the dominantly of ϕ ($p = \frac{1}{\sqrt{2}}$ ($\bar{u}\Gamma_t^A u + d\bar{u}_t^A d$), $\mathcal{O}_A(t) = s\Gamma_t^A s$, where u, operators to construct two-point conclusions of the form $G_{AB}^{d'g}(t', t) = \langle 0 | O_A^{d'}(t') O_B^{m'}(t) | 0 \rangle$ which, after integration of the quark fields, can be composed from *connected* com-ponents diagonal in quark flavor

The quark fields in \mathcal{O} are acted upon by a "distillation spectrum and study the hidden-flavor composition of the states using lattice QCD computations. This is a lattice gauge configurations with dynamical light and intro quark and gluon modes that dominate low mass in order that the flavor mixing appearing to relator contributions that distinguish isoscalars from sorelator contributions that distinguish isoscalars from inter-while evaluation of the signal balanced typically diminish into noise at small Euclidean inter-schede typically diminish in The quark fields in \mathcal{O} are acted upon by a "distilla-



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MOTIVATION









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through quark sector of isoscalar mesons we come and hidden-flavor content of isoscalar mesons in QCD. Empirically it is found that many low-lying isoscalar mesons come in identifiable pairs with a strong prefer-ence for ideal flavor mixing; prominent examples include $\frac{1}{\sqrt{2}}(|u\bar{u}\rangle + |d\bar{d}\rangle)$ we is estimated to be below 1%. Sim-ilarly the tensor mesons, $f_2(1270), f_2(1525)$, where the lighter state decays almost entirely into $\pi\pi$ and the heav-lighter state decays almost entirely into $\pi\pi$ and the heav-lighter state decays almost entirely into $\pi\pi$ and the heav-lighter state decays almost entirely into $\pi\pi$ and the heav-lighter state decays almost entirely into $\pi\pi$ and the heav-lighter state decays almost entirely into $\pi\pi$ and the heav-lighter state decays almost entirely into $\pi\pi$ and the heav-lighter state decays almost entirely into $\pi\pi$ and the heav-lighter state decays almost entirely into $\pi\pi$ and the heav-lighter state decays almost entirely into $\pi\pi$ and the heav-lighter state decays almost entirely into $\pi\pi$ and the heav-lighter state of $SU(3)_F$ which have lowest quark content $\frac{1}{\sqrt{3}}(|u\bar{u}\rangle + |d\bar{d}\rangle - 2|s\bar{s}\rangle)$ and $\frac{1}{\sqrt{3}}(|u\bar{u}\rangle + |d\bar{d}\rangle + |s\bar{s}\rangle)$ re-tractions for the state state state state state states and suggested interpretations featuring light and strange has suggested interpretations featuring light and strange $Q\bar{q}$, $q\bar{q}\bar{q}$ states, glueballs and meson-meson molecules [2].

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tical precision [3–5]. Glue J^{PC} with typically low statistical precision [3–3]. Other ball studies, which produce exceptionally clean spectra in the quark-less Yang-Mills case [6], become challenging in QCD through strong coupling to the quark sector [7]. In this letter we present the isoscalar meson spectrum for a single choice of light and strange quark masses, lat-for a single choice of light are multiple J^{PC} , excluding J^{PC} with typically low statis for a single choice of light and stra for a single choice of light and strange quark masses, later tice spacing and volume across multiple J^{PC} , excluding the 0⁺⁺ case which is of sufficient interest to justify a separate publication of its own. This extends the work separate publication of its own. This extends the work reported in [8, 9] for isovector and kaonic mesons, taking advantage of many of the techniques developed therein. *Lattice technology:* We compute the spectrum of isoscalar mesons using a basis of operators of the form $O(1) = \frac{1}{2\pi} \left(\frac{1}{2\pi} \frac{\Lambda}{2\pi} + \frac{1}{2\pi} \frac{\Lambda}{2\pi} \right) O^{*}(0) = \frac{1}{2\pi} \frac{\Lambda}{2\pi}$ where π isoscalar mesons using a basis of operators of the form $\mathcal{O}_{A}^{t}(t) = \frac{1}{\sqrt{2}} \left(\overline{u} \Gamma_{t}^{A} u + \tilde{d} \Gamma_{t}^{A} d\right), \mathcal{O}_{A}^{t}(t) = \bar{s} \Gamma_{t}^{A} s, \text{ where } u,$ d, and s are the up, down and strange quark fields, and the Γ_{t}^{A} are operators acting in space, color, and Dirac spin space [10] on a time slice, t. We combine these operators to construct two-point correlators of the form $\sigma^{a}(u) = \frac{1}{\sqrt{2}} \frac{(u)\sigma^{a}(u)\sigma^{a}(u)}{(u)\sigma^{a}(u)}$, which after integration operators to construct two-point correlators of the num $C_{AB}^{eq}(t',t) = \langle 0 | O_A^{eq}(t') O_B^{eq}(t) | 0 \rangle$ which, after integration of the quark fields, can be composed from *connected* com-

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MOTIVATION



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MOTIVATION



The $\eta\pi$ and $\eta'\pi$ channels are ideal for searches of spin-exotic hybrids

- Only odd-L waves in $\eta^{(\prime)}\pi$ provide access to exotic quantum numbers
 - simplistic 2-body final states

- historically, consistent observations of exotic resonances signal observed



8







Newport News, Virginia, USA



- designed to reconstruct final state particles from $\gamma p \rightarrow pM$
- 4 polarization orientations

D

- *GlueX-I* collected $L = 125 \ pb^{-1}$ in *coherent peak*
- GlueX-II ~ 3-4 times more (currently ongoing)

Photoproduction \Rightarrow *extremely* versatile

- access to large range of resonances
- complementary to hadroproduction (COMPASS, etc.)



Start simple to understand production of less complex hadrons - study background, acceptance, non-resonant contributions, etc.





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Just accepted for publication (PRC)!

Assume $a_2(1320)$ and $a_2(1700)$ are text book Breit-Wigner resonances

- share only 1 common phase parameter for each in the D_{waves}
- S_{wave} contributions more complicated
 - define mass independent piecewise parameterization
- Individual fit results across -t
 - coherent sums of (+) and (-) reflectivities



- + / - reflectivity \rightarrow natural / unnatural



Why?

Dominant contribution in the $\eta\pi^0$ **channel**

- reasonably isolated
- limited P_{Wave} contribution predicted
- use as reference for search of exotic π_1 in $\eta'\pi$

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Decent agreement between JPAC predictions !

- the first measurement of the $a_2(1320)$ polarized photoproduction cross section





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Nature of strong interactions:

- governed by non-perturbative QCD
- allows resonance formation and decay across multiple channels

Motivation from experimental reality \Rightarrow



- each final state provides only partial access to the underlying pole structure

highly populated spectrums

overlapping & interfering resonances

- resonances (peaks) not always appear as peaks (resonances)

Overall, single channel analyses cannot fully disentangle complex interference or threshold behavior

> **Pole structure is process-independent** (the resonance's nature is fixed)

. production and decay can shape the spectrum, but not the resonance itself



WHY COUPLE CHANNEL EFFECTS ARE IMPORTANT

CITES IN THE REAL PROPERTY INTERNAL PROPERTY $\psi(2S) J/\psi$ • • • **Theory Prediction Example** - 3-channel fit-1 175 --- 3-channel fit-2 ····· DPS 150 $- - m_{J/\psi} + m_{\psi(2S)/\psi(3770)}$ (VeV 15 Fit range LHCb data 8 100 Events Dong et al. , ht. 126 (2021) 75[50 25 $J/\psi J/\psi \rightarrow 2\mu^+ 2\mu^-$ 0 E 7.59.0 6.57.0 8.0 8.5 **Thresholds** $M_{J/\psi J/\psi}$ [GeV] 15 Mellon







- coupled channel fit to both $\eta^{(\prime)}\pi$ systems
- describes dominate a_2 resonances and the π_1



PREVIOUS THEORY COUPLED-CHANNEL RESULTS

Modeled amplitudes using the analytic, unitary *N/D* formalism





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2 poles or 1 pole ?



PREVIOUS THEORY COUPLED-CHANNEL RESULTS

Modeled amplitudes using the analytic, unitary *N/D* formalism











- coupled channel fit to both $\eta^{(\prime)}\pi$ systems
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PREVIOUS THEORY COUPLED-CHANNEL RESULTS

Modeled amplitudes using the analytic, unitary N/D formalism









Numerator







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Denominator





Code developed to perform JPAC's N/Dmethod to GlueX data

Parameterization is universal, can use these to fit photoproduced $\eta\pi$ and $\eta'\pi$!

- numerical evaluation of amplitudes from the formalism produces correct line shapes from A. Rodas, et al.

Note: currently assumes Pomeron exchange and normalization by the π beam momentum q

JPAC correcting this for GlueX

















- lines shapes remain consistent to expected pole positions
- extremely small P_{wave} in $\eta\pi^0$ channel compared to $\eta'\pi^0$ —



N/D MONTE CARLO FITS

Input-Output check with generated signal Monte Carlo for photoproduction kinematics using coupled channel approach





consistent with recent first photoproduced upper limit cross sections of the spin exotic candidate

F. Afzal et al. [GlueX Collab], Phys. Rev. Lett. 133, 261903 (2024)











- P_{wave} contribution is non-zero in $\eta\pi^0$ channel





Input-Output check with generated signal Monte Carlo for photoproduction kinematics using coupled channel approach



N/D SINGLE CHANNEL MONTE CARLO FITS

GlueX has collected large quantity of photoproduced data

- recent results extracted a_2 cross section which will be used as a reference signal
- can analyze production mechanisms using polarization info
- strong effort to look for exotic hybrid π_1 meson in $\eta^{(\prime)}\pi$ systems using several different analysis methods
- first look into utilizing coupled channel methods at GlueX other parameterizations (KMatrix, etc.) also being leveraged
- **Next immediate steps:**

GLUE

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- further analyze both neutral and charged $\eta^{(\prime)}\pi$
 - extract a_2^- cross section, perform moment extraction, etc.
- continue I/O studies with Monte Carlo \rightarrow perform coupled fits to data

GlueX acknowledges the support of several funding agencies and computing facilities



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EXCITING TIMES FOR **EXOTICS SEARCHES!**









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BACKUP SLIDES



Describes all two-pseudoscalar systems (i.e. all $\eta^{(\prime)}\pi$)

 $\phi_{\eta^{(\prime)}}$

New basis
$$\to Z_l^m(\Omega, \Phi) = Y_l^m(\Omega) e^{-i\Phi}$$

Described by 3 angles: $\cos \vartheta_{\eta^{(\prime)}}$

in the resonance frame

btw the polarization and production plane

Reflectivity corresponds to exchange being natural (+1) and unnatural (-1) parity

4x more amplitudes than hadro-production

$$\Rightarrow \mathcal{I}(\Omega, \Phi) = 2\kappa \sum_{k} \left\{ (1 - P_{\gamma}) \left| \sum_{l,m} \left[l \right]_{m}^{(-)} \mathscr{R}e[Z_{l}^{m}(\Omega, \Phi)] \right|^{2} + (1 - P_{\gamma}) \left| \sum_{l,m} \left[l \right]_{m}^{(+)} \mathscr{I}m[Z_{l}^{m}(\Omega, \Phi)] \right|^{2} + (1 + P_{\gamma}) \left| \sum_{l,m} \left[l \right]_{m}^{(-)} \mathscr{I}m[Z_{l}^{m}(\Omega, \Phi)] \right|^{2} \right\}$$



V. Mathieu et al. [JPAC], PRD 100, 054017 (2019)







In QFT \rightarrow resonances correspond to poles of the S-matrix in the complex energy plane

- these poles lie off the real energy axis, reflecting the unstable nature of resonances

- not directly visible, but influence observables (i.e. cross sections)
- resonance position and width \rightarrow encoded in complex pole location

Breit-Wigner functions are the historical standard for describing resonances

- algebraically simple
- work well for isolated, narrow resonances

useful first approximation!

EPS-HEP GLUE **Zachary Baldwin**

BEYOND THE BREIT-WIGNER



But...

- fails to conserve total probability in multi-channel scattering
- do not account for:
- 1) coupled-channel effects
 - 2) overlapping resonances
 - **3** nearby thresholds
- To understand what a true resonance is, we must ask where its pole position lies ... not where its bump appears!







Overlapping resonances interfere differently depending on model

- **BW**: underestimates interference
- CC: enhances the first peak through self-consistent interference across poles



PHASE MOTION

ARGAND LOOP





Overlapping resonances interfere

- BW: no threshold structure and ignores threshold effects
- CC: shows a non-analytic phase jump showcasing multiple channel feedback

3.0 **-**2.5 **-**2.0 [rad] δ 1.0 · 0.5 -1.2 1.0

INTENSITY EVOLUTION



differently depending on model



ARGAND LOOP





INTENSITY EVOLUTION

PHASE MOTION



Overlapping resonances interfere differently depending on model

- **BW**: erratic, non-unitary motion
- CC: clean, unitary counter-clockwise trajectory





Formalism following the approach in *Rodas*, A et al gives the production amplitude as:

Angular Momentum Barrier Factors

 $A_i^J(s) =$

KMatrix Analytic Denominator









In order to use the previous results on photoproduced data - need to fix the following parameters…

$$n_{k}^{J}(s) = \sum_{i=0}^{3} a_{i}^{(J,k)} T_{i} \left(\frac{s}{s+1}\right)$$

$$K_{ki}^{J}(s) = \sum_{R} \frac{g_{k}^{J,R} g_{i}^{J,R}}{m_{R}^{2} - s} + c_{ki}^{J} + c$$

$$A_{i}^{J}(s) = \beta^{P} \cdot q^{J-1}(s) \cdot p_{i}^{J}(s) \cdot \sum_{k=1}^{3} \left(\sum_{n=0}^{3} a_{n}^{(J,k)} T_{n}\left(\frac{s}{s+1}\right) \right) \cdot \left[D^{J}(s)^{-1} \right]_{ki}$$



- $a \rightarrow$ **Chebyshev Coefficients**
- 8 \rightarrow **Final State Couplings**
- $c, d \rightarrow$ **Backgrounds in** *K***-Matrix**



··· and the only parameters floated in the fit are the complex photocouplings ····

 \cdots in each reflectivity (+/-)





N/D parameters from JPAC

| | | K-matrix background | | | | |
|---------------------|----------------|---------------------|----------------------------|-----------------------|---|-------------------|
| supplemental | | | $c^P_{\eta\pi,\eta\pi}$ | -15.43 | | |
| | | | | -14.77 ± 7.22 | Resonating terms | |
| Coefficient | $\eta\pi$ | $\eta'\pi$ | $c^P_{\eta\pi,\eta'\pi}$ | -67.22 | $g^P_{n\pi}$ | -0.68 |
| a_0^P | 408.75 | -47.05 | | -65.28 ± 13.91 | | -0.55 ± 0.38 |
| | 356 ± 334 | -43 ± 39 | $c^P_{\eta'\pi,\eta'\pi}$ | -190.73 | $g^P_{n'\pi}$ | -13.12 |
| a_1^P | -632.57 | 65.84 | | -184.19 ± 38.21 | | -13.12 ± 0.93 |
| | -547 ± 534 | 59 ± 63 | $d^P_{\eta\pi,\eta\pi}$ | 1.82 | $m_{P_{1}}^{2}$ | 3.52 |
| a_2^P | 281.48 | -20.96 | | 1.93 ± 2.24 | | 3.52 ± 0.08 |
| | 240 ± 255 | -17 ± 30 | $d^P_{\eta\pi,\eta'\pi}$ | 7.64 | $g^D_{n\pi 1}$ | 5.63 |
| a_3^P | -57.98 | 1.20 | | 7.59 ± 5.09 | | 5.64 ± 0.34 |
| D | -47 ± 63 | 0 ± 8 | $d^P_{\eta'\pi,\eta'\pi}$ | 63.85 | $g^{D}_{n'\pi 1}$ | -3.77 |
| a_0^D | -247.80 | 230.92 | | 60.54 ± 18.59 | $\mathcal{O}\eta$ $\mathfrak{n},\mathfrak{l}$ | -3.78 ± 0.10 |
| D | -247 ± 28 | 233 ± 79 | $c^D_{\eta\pi,\eta\pi}$ | -2402.56 | $m_{D_{1}}^{2}$ | 1.86 |
| a_1^D | 413.91 | -290.66 | | -2385.05 ± 273.87 | D,1 | 1.86 ± 0.02 |
| Δ | 415 ± 39 | -290 ± 125 | $c^{D}_{\eta\pi,\eta'\pi}$ | 462.60 | $g^D_{n\pi 2}$ | 147.79 |
| $a_2^{\mathcal{D}}$ | - 190.94 | 1/6.88 | | 469.55 ± 55.87 | $\circ\eta\eta\iota,$ 2 | 147.17 ± 9.88 |
| a D | -192 ± 39 | $1//\pm 83$ | $c^{D}_{n'\pi,n'\pi}$ | -86.60 | $g^D_{n'\pi 2}$ | -33.39 |
| a_3 | 39.23 | -3.82 1 + 62 | | -92.25 ± 28.11 | 0η π ,2 | -34.07 ± 3.4 |
| | 01 ± 29 | -1 ± 02 | $d^D_{\eta\pi,\eta\pi}$ | -614.58 | $m_{D_{2}}^{2}$ | 8.06 |
| | | | | -608.35 ± 49.32 | D,2 | 8.06 ± 0.30 |
| | | | $d^D_{\eta\pi,\eta'\pi}$ | 164.72 | | |
| | | | | 166.85 ± 17.46 | | |
| | | | $d^D_{n'\pi.n'\pi}$ | -42.19 | | |
| | | | | -44.45 ± 11.59 | | |

EPS-HEP Zachary Baldwin





 0.55 ± 0.38

 3.12 ± 0.95

 3.78 ± 0.10

 7.17 ± 9.88

 4.07 ± 3.41