SEARCH FOR EXOTIC QUANTUM- NUMBER MESONS IN THE EXPERIMENT

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On behalf of the GlueX Collaboration
• The GlueX Experiment
• Exotic Quantum Number Mesons
• Photoproduction
• Searching for Exotics
• $J/\psi$ Photoproduction
• **Search for hybrid mesons.**
  • Gluonic DOF.
  • Predicted by LQCD.

• Linearly-polarized photon beam.
  • Unexplored regime.

• Hermetic detector.
  • Exclusive reaction.

• Very high statistics.
  • 125 pb^{-1} in Phase I

**NIM A987, 164807 (2021)**
Coherent bremsstrahlung of 12 GeV electron beam on 50µm diamond radiator. Linearly polarized photons in coherent peak ($E_\gamma$ from 8.4 to 9 GeV).

The beam is energy tagged, has its polarization measured, and the flux is determination close to the GlueX detector.

Linearly-polarized photons act as a filter on the naturality of the exchange mechanism. Photon beams are unique: $J=1$, through VMD are effectively beams of $\rho$, $\omega$ and $\phi$ mesons.
QUARK MODEL MESONS

Combine two spin ½ objects to $S=0$ or $S=1$

Orbital angular momentum of two quarks: $L=0,1,2,3,\ldots$

Total angular momentum, $J=L+S$: $J=0,1,2,3,\ldots$

Spatial Reflection Symmetry: Parity $P=(-1)^L$

Quark-antiquark Reflection: C-parity $C=(-1)^{L+S}$

Mesons are characterized by nonets of $J^{P(C)}$

Exotic Quantum Numbers: $J^{PC}=0^-, 0^+, 1^+, 2^-$

Allowed $J^{PC}$

- $L=2, S=0$, $J^{PC}=2^+$
- $L=1, S=0$, $J^{PC}=1^-$
- $L=1, S=1$, $J^{PC}=2^{++}$
- $L=2, S=1$, $J^{PC}=3^{--}$
- $L=2, S=0$, $J^{PC}=2^-$
Light-quark mesons, u,d,s and their antiquarks.

Shown are are I=0 and I=1 states.

Color shows mixing of I=0 states.

Large Gluonic Component
Light-quark mesons, $u,d,s$ and their antiquarks.

Shown are are $I=0$ and $I=1$ states.

**Color** shows mixing of $I=0$ states.

Large Gluonic Component

$$\frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d})$$

$$\frac{1}{\sqrt{2}} (u\bar{u} - d\bar{d})$$

$$(s\bar{s})$$

**Exotics**

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

PRD83, 111502 & PRD88, 094505
Lattice QCD suggests 5 nonets with exotic quantum numbers:
1 nonet of $0^{+-}$ exotic mesons
2 nonets of $1^{-+}$ exotic mesons
2 nonets of $2^{+-}$ exotic mesons

Lattice QCD results are consistent with the gluonic field behaving like a $J^{PC}=1^{+-}$ constituent with a mass $\sim 1-1.5$ GeV/c².
EXOTIC HYBRID MESONS

Experimental Evidence for the I=1 $\pi_1(1600)$.

$\pi_1(1600)$ reported in:
- $\eta'\pi$: COMPASS/JPAC, E852, VES, CLEO-c
- $\rho\pi$: COMPASS, E852
- $b_1\pi$: VES, E852, CBAR
- $f_1\pi$: VES, E852

JPAC $\eta\pi / \eta'\pi$ coupled channel fit to and partial waves in pion production measured by COMPASS: $\pi_1(1600)$
- Mass: $1564 \pm 24 \pm 86$ MeV/c$^2$
- Width: $492 \pm 54 \pm 102$ MeV/c$^2$

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WHERE DO WE LOOK?

Where are all the states?
Spin 0: $b_0, h_0, h_0'$
Spin 1: $\pi_1, \eta_1, \eta_1'$
Spin 2: $b_2, h_2, h_2'$

Photoproduction could couple to all of these through simple exchange mechanisms: $\pi, \eta, \rho, \omega, P, b_1, h_1$

LQCD predicts the decays of the $\pi_1$, $b_1 \pi$ dominant, much smaller rates to $\eta' \pi$, $\rho \pi$ and $f_1 \pi$

Phys. Rev. D 103, 054502 (2021)
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For the others, look at “allowed” decay modes.

First searches
Need statistics
Difficult
SEARCHING FOR HYBRIDS

• Understand production mechanisms:
  • Natural $J^p=0^+, 1^-, 2^+, ...$ and unnatural $J^p=0^-, 1^+, 2^-, ...$ exchanges.
  • Linear Photon Polarization!
  • Beam asymmetry $\Sigma$, SDMEs $\rho^i_{jk}$, ....

• Understand Acceptance
  • SDMEs, Cross sections, ....

• Reproduce known results
  • Start with $\eta\pi$ and $\eta'\pi$
BEAM ASYMMETRY $\Sigma$

\[ Y_{\parallel}(\phi, \phi_\gamma = 0) \propto (1 - P_\parallel \Sigma \cos 2\phi) \]
\[ Y_{\perp}(\phi, \phi_\gamma = 90) \propto (1 + P_\perp \Sigma \cos 2\phi) \]

Production mechanism:
unnatural at low $|t|$, natural at high $|t|$.

Exchange $J^{PC}$

\[ 1^{--} : \omega, \rho \]
\[ 1^{+-} : b, h \]
• The Spin-Density matrix $\rho$ of vector mesons describes the meson’s polarization.
• Nine elements can be measured using decay angular distributions.
• Sensitive to production mechanisms.

$P_\sigma = 2\rho^1_{1-1} - \rho^1_{10}$

- $P_\sigma = 1$ Natural parity exchange:
  - $0^{++}$, $1^-$, $2^{++}$, ...
- $P_\sigma = -1$ Unnatural parity exchange:
  - $0^+$, $1^+$, $2^+$, ...

$\gamma p \rightarrow \rho p$

$\gamma p \rightarrow \omega p$
SEARCH FOR EXOTICS

Highest statistics on $\pi_1(1600) \rightarrow \eta'\pi$ from COMPASS

$\pi^- p \rightarrow p \eta\pi^-$  $\pi^- p \rightarrow p \eta'\pi^-$

COMPASS: strong exotic wave in the $\eta'\pi^-$, but not in the $\eta\pi^-$ data.

JPAC: Extracted the pole position of the $\pi_1(1600)$ from the COMPASS amplitudes.

Mass: $1564 \pm 24 \pm 86$ MeV
Width: $492 \pm 54 \pm 102$ MeV

SEARCH FOR EXOTICS

Comprehensive approach:
\[ \gamma p \rightarrow p \eta \eta' \pi^0 \]
\[ \gamma p \rightarrow \Delta^{++} \eta / \eta' \pi^- \]
\[ \eta \rightarrow \gamma \gamma, \pi^+ \pi^- \pi^0 \]

Close collaboration with theory to develop analysis tools.
Amplitude Analysis of low-mass $\eta\pi^0$ system

- Large S-wave contributions.
- The $a_2(1320)$ produced dominantly in the $D_2^+$ partial wave.

Small wave set includes positive and negative reflectivity S and D waves.
OTHER CHANNELS

Exotic searches now looking at vector-pseudoscalar final states

\[ \pi_1 \rightarrow \pi \rho \]
\[ \eta_1' \rightarrow K^*K \]
\[ b_2 \rightarrow \omega \pi, \rho \eta \]
\[ h_2 \rightarrow \rho \pi, \omega \eta \]

- Possible exotic decays.
- No narrow structures observed in the 1.8 to 2.3 GeV mass region.
- Partial wave analysis needed to search for broad states.

Related talks:
- Zisis Papandreou next: \( \omega \pi \) cross sections.
- Karthik Suresh earlier today: \( \omega \pi \) amplitude analysis.
\( \gamma p \rightarrow p J/\psi \)

Measure cross section near threshold.

Exclusive reaction \( \gamma p \rightarrow J/\psi p \rightarrow e^+e^-p \)

Preliminary

number of \( J/\psi \)’s 2141 ± 57
OPPORTUNISTIC PHYSICS

\( \gamma p \rightarrow p J/\psi \)

- Published a portion (469 \( J/\psi \) events) of the Phase-I data.
- 27% Normalization uncertainty.
- Set upper limits on LHCb pentaquark production.
- The full data set is nearing publication.

PRL 123, 072001 (2019)
OPPORTUNISTIC PHYSICS


\[ \gamma p \rightarrow p J/\psi \]

Du et al., EPJC 80, 1053 (2020)

mass radius: \( R_m = 0.55 \pm 0.03 \) fm
charge radius: \( R_c = 0.8409 \pm 0.0004 \) fm

More data closer to the threshold is needed

Calculated cross section energy dependence including open charm loops Higher precision data is needed
SUMMARY

• The GlueX Phase I 125 pb-1, Phase II with DIRC will be about a factor of 5.

• Beam asymmetry measurements allow us to study production mechanisms of simple final states.

• Spin-density matrix elements probe more complicated production.

• Initial results on the $\eta\pi$ and $\eta'\pi$ system, key first exotic search.

• Next searches focus of vector-pseudoscalar.

• Very interesting results on $J/\psi$ photoproduction.
Backup Slides
Threshold production is experimentally clean, ideal for studying J/ψ+N interaction.

Study coupling of resonant J/ψ+p states to photon.

\[ \Lambda_b \rightarrow J/\psi \ p \ K^- \]

s-channel photoproduction probes nature of 5-quark interaction!
First $J/\psi$ cross section measurement at threshold, 27% normalization uncertainty, 3x as much data collected.

Model-dependent upper limits at 90% CL:

- $\text{Br}(P_c(4312) \rightarrow J/\psi \ p) < 4.6\%$
- $\text{Br}(P_c(4440) \rightarrow J/\psi \ p) < 2.3\%$
- $\text{Br}(P_c(4457) \rightarrow J/\psi \ p) < 3.8\%$