Beam Asymmetries from Light Scalar Meson Photoproduction on the Proton at GlueX

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The structure of light scalar meson states (spin 0, even parity) is poorly understood.

Large widths mean states have significant overlap with background.

Further complicated by proximity to $K\bar{K}$ and $\eta\eta$ thresholds.
Light Scalar Mesons

\( h_0(980) \)

\[ I^G(J^{PC}) = 0^+(0^{++}) \]

Mass \( m = 990 \pm 20 \text{ MeV} \)

Full width \( \Gamma = 10 \text{ to } 100 \text{ MeV} \)

\( h_0(980) \) DECAY MODES

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Fraction ( \Gamma_i/\Gamma )</th>
<th>( \rho ) (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi \pi )</td>
<td>dominant</td>
<td>476</td>
</tr>
<tr>
<td>( K \bar{K} )</td>
<td>seen</td>
<td>36</td>
</tr>
<tr>
<td>( \gamma \gamma )</td>
<td>seen</td>
<td>495</td>
</tr>
</tbody>
</table>

\( a_0(980) \)

\[ I^G(J^{PC}) = 1^-(0^{++}) \]

Mass \( m = 980 \pm 20 \text{ MeV} \)

Full width \( \Gamma = 50 \text{ to } 100 \text{ MeV} \)

\( a_0(980) \) DECAY MODES

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Fraction ( \Gamma_i/\Gamma )</th>
<th>( \rho ) (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta \pi )</td>
<td>dominant</td>
<td>319</td>
</tr>
<tr>
<td>( K \bar{K} )</td>
<td>seen</td>
<td>\dagger</td>
</tr>
<tr>
<td>( \gamma \gamma )</td>
<td>seen</td>
<td>490</td>
</tr>
</tbody>
</table>

Chin. Phys C40, 100001 (2016)

- Phenomenological models describe the light scalars as anything from \( q\bar{q} \) to glueballs and tetraquarks.
- Precision measurements of the properties of observed states is the key to understanding their nature in quark-gluon terms.
- Specifically, photoproduction data of light scalars could provide helpful insights.
Light Scalar Mesons

- The $\pi\pi$ decay of $f_0(980)$, and the $\eta\pi$ decay of $a_0(980)$, both accessible through the four photon final state, are thought to be a powerful tool to discriminate between models.
- Both states lie close to $K\bar{K}$ threshold, which has so far made accurate determination of resonance properties difficult.
- For the purposes of this talk, we will focus on the $\eta\pi$ final state.
Theoretical Insights (JPac)

**production:** natural exchanges

**line shape:** Breit-Wigner form

**parameters:** arbitrary

Small exotic wave, not apparent in the diff. cross. section

VM et al (JPAC), in preparation
Contributing waves in the model can be expressed in terms of the beam asymmetry.

Possible influence of an exotic state is more pronounced at small angles in the Gottfried-Jackson frame.
Theoretical Insights (JPac)
Theoretical Insights (Donnachie, Kalashnikova)

- Model using reggeised $\rho$ and $\omega$ exchange employed to calculate photoproduction amplitudes for $a_0(980)$ and $f_0(980)$

- Cross section predictions available for light scalar meson production

\[ \frac{d\sigma}{dt} \]

\[ a_0(980) \]

\[ 3.5 \text{ GeV} \]

\[ 9 \text{ GeV} \]

\[ f_0(980) \]

\[ 3.5 \text{ GeV} \]

\[ 9 \text{ GeV} \]

Phys Rev C93 (2016) 025203

- Model also provisionally predicts beam asymmetry for these mesons
- S-wave scattering amplitude from a coupled-channel lattice calculation
- Usual caveats about unphysical quark masses
- Suggestions that something significant happens at $K\bar{K}$ threshold
- Possibly an $a_0(980)$-like resonance, coupled to $K\bar{K}$ and $\eta\pi$

Jefferson Lab - US DoE facility in Newport News, VA

- Superconducting RF accelerator with primary electron beam of up to 12 GeV
- Four experimental halls, with simultaneous beam delivery
- Real photon beam experiments in Hall D, using a secondary bremsstrahlung photon beam in the GlueX experiment
Jefferson Lab - US DoE facility in Newport News, VA

Superconducting RF accelerator with primary electron beam of up to 12 GeV

Four experimental halls, with simultaneous beam delivery

Real photon beam experiments in Hall D, using a secondary bremsstrahlung photon beam in the GlueX experiment
12 GeV electron beam produces real photon beams via bremsstrahlung radiation off a radiator (Aluminium or Diamond) up to 9 GeV.

Photon energy tagged by detecting energy-degraded electron in one of two devices in the tagger focal plane.

Ancillary devices to determine flux and polarisation.

Polarised photon beams from coherent remsstrahlung off diamond radiators.
GlueX Beamline

- Beam is collimated to enhance polarised component (typically around 40% polarisation at 9 GeV)
- Polarisation planes rotated by 90 degrees to constrain systematics
- Referred to as PARA (parallel) and PERP (perpendicular)
Real photon beam interacts with target
Charged and neutral particle detection in a hermetic solenoid-based detector
Uniform acceptance over $4\pi$ solid angle
Recent upgrade has added a DIRC
The $\eta\pi$ Channel

- This work focuses on studying beam asymmetries of the $\eta\pi$ channel, where $\eta$ and $\pi$ each decay to a pair of photons

$$\gamma p \rightarrow p\eta\pi \rightarrow p\gamma\gamma\gamma\gamma$$

- This will later lead to asymmetry measurements of the $a_0(980)$ and $a_2(1320)$ mesons, both of which are seen in the four photon final state of $\eta\pi$

- Kinematic fit used to identify particles and filter data

- Cuts applied on vertex position, $\frac{dE}{dx}$ cut in the drift chamber for proton, and photon beam energy
**η** and **π**$^0$ Identification

- **π**$^0$ and **η** distributions from diphoton invariant masses

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**Graph 1:** $m(2\gamma,\text{pair2})$ vs $m(2\gamma,\text{pair1})$

- $\pi^0\eta$
- $\pi^0\pi^0$
- $\pi^0\eta$

**Graph 2:** $m(2\gamma,\text{pair2})$ vs $m(2\gamma,\text{pair1})$

- $\eta\eta$

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*Preliminary*
Even assuming perfect particle identification, different processes can result in the same final state.

This is particularly true as the number of particles in the final state increases.

In the reaction $\gamma p \rightarrow p\eta\pi$, the final state particles could arise from the production of an intermediate meson ($a_0(980) \rightarrow \eta\pi$), or baryon ($\Delta^+ \rightarrow p\pi^0$).
With further event selection processes, e.g. vetoing baryon resonances, produce cleaner meson samples
Invariant Mass Distributions

- Invariant Mass of $\eta\pi$, showing clear signals of $a_0(980)$ and $a_2(1320)$
- Also suggestions of a higher mass state, possibly $a_2(1700)$
- Events with small GJ angles ($\cos \Theta_{GJ}$ close to 1) are severely suppressed
The competing baryonic and mesonic processes have very different reaction kinematics.

In the centre of mass frame, it is possible to separate them.
This isn’t a new idea, it was first proposed and studied fifty years ago by Leon Van Hove.

His basic premise is that at sufficiently high centre-of-mass energy, phase space is dominated by longitudinal components of particle momenta.

Transverse components can be neglected, reducing dimensionality of phase space.
Van Hove Plots

- This gave rise to the Longitudinal Phase Space plot, a way of visualising reaction kinematics of an n-particle final state in an n-1 dimensional plane.
- For example, in a three particle final state, the longitudinal phase space can be represented on a two dimensional plane.

- We can define co-ordinates on the van Hove plot analogously to polar co-ordinates via the longitudinal momentum components of the final state particles:

\[
X = q \cos(\omega) \\
Y = q \sin(\omega)
\]
Interpretation

- The axes divide the longitudinal phase space into six sectors.
- Each sector corresponds to specific directions of travel of the final state particles in the CM frame.
- The arrows on the axes show the forward travel of each labelled particle.
- For example, the bottommost sector has $\eta\pi$ going forward and proton going backward.
Insights from Van Hove

- Can also visualise the event samples in a Van Hove plot

- Cuts have removed much of the unwanted baryon processes, but at a cost of signal
Optimising $p\eta\pi^0$ Selection

- Van Hove angle against invariant mass of particle pairs

- Here, the $a_0(980)$ and $a_2(1320)$ can be seen, and the baryon processes are also visible

- Rather than cut on Van Hove angle, we can use these plots to inform baryon veto cuts, and verify them by examining the Van Hove plot
Optimising $p\eta\pi^0$ Selection

- Loosen the Baryon cuts, and re-examine VH distribution

- Van Hove plots can be a useful tool to verify event selection
In JLab and GlueX Analysis

**Introduction**

- Invariant Mass of $\eta\pi$, with looser baryon cuts
- The $a_0(980)$ and $a_2(1320)$ remain, as does the hint of something else at 1.7 GeV
- $\cos \theta_{GJ}$ vs invariant mass preserves more small angle events using the new cuts

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**In JLab and GlueX Analysis**

**Beam Asymmetry**

**Conclusions and Outlook**

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**Invariant Mass Distribution, post optimisation**

- Invariant Mass of $\eta\pi$, with looser baryon cuts
- The $a_0(980)$ and $a_2(1320)$ remain, as does the hint of something else at 1.7 GeV
- $\cos \theta_{GJ}$ vs invariant mass preserves more small angle events using the new cuts
Yields of PARA and PERP data are used to compute an asymmetry

\[ A(\phi) = \frac{N(\text{PARA}) - N(\text{PERP})}{N(\text{PARA}) + N(\text{PERP})} \approx P_{\text{lin}} \Sigma \cos(2\phi) \]

To account for differing fluxes and beam polarisations, the PARA/PERP asymmetry distributions can be fit in each bin with a function of the form

\[ A(\phi) = \frac{F_R - 1 + \frac{F_R P_R + 1}{P_R + 1} 2 \bar{P}_\Sigma \cos(2(\phi - \phi_0))}{F_R + 1 + \frac{F_R P_R + 1}{P_R + 1} 2 \bar{P}_\Sigma \cos(2(\phi - \phi_0))} \]

PARA/PERP flux and beam polarisation ratios are parameters of the fit, along with \( \bar{P}_\Sigma \) and \( \phi_0 \)
Beam Asymmetry

- Example fit for mass bin spanning the $a_0(980)$ meson
- Magnitude of the cosine term gives us a measurement of $P_{\gamma \Sigma}$

- We measure values of $F_R$ and $P_R$ using detectors in our beamline (Pair Spectrometer and Triplet Polarimeter)
- Use them to constrain fit parameters
- The value of $\phi_0$ is reaction independent and measured from reactions with higher statistics
Beam Asymmetry on $\eta\pi$

- Beam Asymmetries with $\eta\pi$ invariant mass
- All $\cos \theta_{GJ}$, statistical errors only

![Graph: Sigma vs Invariant Mass](image)

\[ \Sigma \text{ vs Invariant Mass} \]
Beam asymmetry of $\eta\pi$ is a useful first measurement to make in this system.

Possible to inform models of the mesons producing this final state.

Partial Wave Analysis envisioned on full phase 1 GlueX data (with tools developed and tested on smaller subsample of the phase I data).

Beam asymmetry measurements of the $a_0(980)$ and $a_2(1320)$ mesons, binned in $-t$, also underway.