Search for exotic states in photoproduction at GlueX

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Abstract. Understanding the hadron spectrum is one of the primary goals of non-perturbative QCD. Many predictions have been experimentally confirmed, but others remain under experimental investigation. Of particular interest is how gluonic excitations give rise to states with constituent glue. One class of such states are hybrid mesons that are predicted by theoretical models and Lattice QCD calculations. Searching for and understanding the nature of these states is a primary physics goal of the GlueX experiment at the CEBAF accelerator at Jefferson Lab in the US. We will give an overview of the experiment, and present the status of the search for a hybrid meson candidate, \(Y(2175)\).

1. Introduction

Mesons in the constituent quark model are color-singlet bound states of a quark \(q\) and antiquark \(\bar{q}\), with quantum numbers \(J^{PC} = 0^{-}, 0^{++}, 1^{--}, 1^{++}, 1^{-+}, 2^{--}, 2^{++}, etc.,\) where \(J\), \(P\) and \(C\) denote total angular momentum, parity and charge conjugation of the fermion system, respectively. This simple picture has successfully described many observed states in the meson spectrum. However, a richer spectrum is allowed by Quantum Chromodynamics (QCD) that includes the gluonic degrees of freedom in the quark and anti-quark system. Since the gluonic field can carry different quantum numbers, this introduces many new states to the spectrum. These include states with quantum numbers: \(J^{PC} = 0^{--}, 0^{+-}, 1^{--}, 2^{+-}, etc.,\) that are not allowed for conventional \(qq\) mesons. The latter are instead referred to as spin-exotic hybrid mesons, and their experimental observation will be a proof of the existence of states beyond the constituent quark model. The hybrid mesons are predicted by many phenomenological models [1]. In addition, Lattice QCD provides predictions for their properties like the mass [2], which can be tested experimentally.

2. Experimental Setup

The GlueX experiment is dedicated to the search for light-mass hybrid mesons, using a high-energy linearly polarized photon beam, produced by a 12 GeV electron-beam through coherent bremsstrahlung on a diamond radiator. By choosing the crystal axis orientation of the diamond, we have collected four data sets, with 2 sets of parallel \((0^\circ/90^\circ)\) and perpendicular \((45^\circ/135^\circ)\) polarization orientations. Using the electron pair and the recoil \(e^-\) from the \((\gamma e^- \rightarrow e^+ e^- e^+)\) scattering on a thin Be foil, the energy of the photon beam is measured by a spectrometer system consisting of a dipole magnet and scintillator arrays, while the polarization is measured by a silicon detector, which is segmented in azimuthal angle. The photon beam impinges on a 30 cm long liquid hydrogen target positioned along the central axis of the detector.
The central region of the detector is contained within a solenoid magnet with \( \sim 2T \) on its central axis. Particles from the primary interaction first pass through the Start Counter, which helps identifying the beam bucket that generated the event. Directly surrounding the Start Counter is the Central Drift Chamber, a straw tube detector, providing tracking and energy loss \((dE/dx)\) information. Downstream of the Central Drift Chamber, the four packages of the Forward Drift Chamber system (planar drift chambers) are located, providing tracking as well as the \( dE/dx \) information. The Barrel Calorimeter is surrounding the tracking devices and is made of lead scintillator fibers. It is sensitive to photons of polar angles between 11° and 126°. Downstream of the solenoid is the Forward Calorimeter, consisting of lead-glass blocks, which covers polar angles from 1° to 11°. In front of the Forward Calorimeter is the Time Of Flight wall, a scintillator bars, providing timing information. For more details about the GlueX detector components and performance, see Ref. [3].

![Figure 1. The GlueX experimental setup.](image)

### 3. Beam Asymmetry Measurements

Understanding the mechanisms of meson photoproduction is critical for disentangling the \( J^{PC} \) quantum numbers of the observed states in the exotic hybrid mesons search. Theoretical models predict that the beam asymmetry \( \Sigma \) is sensitive to the relative contributions from vector \( (1^-/(\rho^0/\omega)) \) and axial-vector \( (1^+(b_1^0/h_1)) \) exchanges in \( \pi^0 \) and \( \eta \) photoproduction Ref. [4].

The exclusive reactions \( \gamma p \rightarrow p\pi^0 \) and \( \gamma p \rightarrow p\eta \) with \( \pi^0/\eta \rightarrow \gamma\gamma \), are studied. The yields for the perpendicular and parallel polarization orientations are given by Eq. 1.

\[
Y_{\parallel/\perp} \propto N_{\parallel/\perp} [\sigma_0 A(\phi) (1 \mp \Sigma \cos 2\phi_p)],
\]

where \( \Sigma \) is the beam asymmetry, \( N_{\parallel/\perp} \) is the flux of photons in the two aforementioned orthogonal orientations, \( \sigma_0 \) is the unpolarized cross section, \( A(\phi) \) is an arbitrary function describing the \( \phi \)-dependent detector acceptance and efficiency, \( P \) is magnitude of the beam polarization and \( \phi_p \) is the azimuthal angle of the production plane defined by the final-state proton.

The orthogonality of the parallel and perpendicular polarization configurations cancels out the \( \phi \)-dependent detector acceptance effects.

\[
\frac{Y_{\perp} - F_R Y_{\parallel}}{Y_{\perp} + F_R Y_{\parallel}} = \frac{(P_{\perp} + P_{\parallel}) \Sigma \cos 2\phi_p}{2 + (P_{\perp} - P_{\parallel}) \Sigma \cos 2\phi_p},
\]
where $F_R = N_\perp / N_\parallel$ is the ratio of the integrated photon flux between perpendicular ($N_\perp$) and parallel polarizations ($N_\parallel$). Figure 3 shows the yield asymmetry as a function of $\phi_p$, which is fit using the functional form in Eq. (2), where the beam asymmetry $\Sigma$ is the only free parameter.

![Figure 2](image2.png)

**Figure 2.** The yield asymmetry, fit with Eq. (2) to extract $\Sigma$.

The beam asymmetry is determined in bins of momentum transfer ($-t$) for $\pi^0$ and $\eta$ photoproduction. The results are shown in Fig. 3.

![Figure 3](image3.png)

**Figure 3.** Beam asymmetry $\Sigma$ for (a) $\gamma p \rightarrow p\pi^0$ and (b) $\gamma p \rightarrow p\eta$ (black filled circles). Uncorrelated systematic errors are indicated by the height of gray bars, whereas the combined statistical and systematic uncertainties are given by the black error bars. The previous SLAC results from data collected at $E_\gamma = 10$ GeV (blue open circles) are also shown along with various Regge theory calculations (see ref. [4] and references therein).

The theoretical models predict a dip near $-t = 0.5$ (GeV/c)$^2$, due to contributions from axial-vector meson exchange matching previous $\pi^0$ measurements at $E_\gamma = 10$ GeV from SLAC. This dip is not observed in the GlueX data, which strongly suggests the dominance of vector meson exchange at this energy. The $\eta$ beam asymmetry measurements are the first above 3 GeV, and are consistent with unity over the measured $-t$ range.

4. Charmonium Photoproduction Near Threshold

The study of near-threshold $J/\psi$ photoproduction can provide information on the gluonic structure of the nucleus, for example through measuring the contribution of the leading order (two-gluon exchange) or higher twist (three-gluon exchange) processes in the production
mechanism [5]. The $J/\psi$ photoproduction can also be used to search for the pentaquark candidates reported by the LHCb experiment in the $J/\psi p$ system from the $\Lambda_c^0 \rightarrow J/\psi pK^-$ decay Ref. [5].

The exclusive reaction $\gamma p \rightarrow p e^+ e^-$ was selected, which includes the narrow $\phi$ and $J/\psi$ peaks, as well as a continuum dominated by the Bethe-Heitler (BH) process. Figure 4 (a) shows the invariant mass spectrum of $e^+ e^-$ data after the event selection. We normalize the $e^+ e^-$ total cross section to that of BH, in the invariant mass range 1.20 - 2.50 GeV, thus minimizing uncertainties from factors like luminosity and common detector efficiencies. The BH diagrams can be calculated to a good accuracy using standard QED calculations (see details in [5]).

![Figure 4](image_url)

**Figure 4.** (a) Electron-positron invariant mass spectrum from the data. The insert shows the $J/\psi$ region fitted with a linear polynomial plus a Gaussian (fit parameters shown). (b) GlueX results for the $J/\psi$ total cross section as a function of the beam energy, together with the Cornell and SLAC data, the theoretical predictions, and the JPAC model. All curves are fitted/scaled to GlueX data only. For these data the quadratic sums of statistical and systematic errors are shown. The overall normalization uncertainty is 27%. (see details in [5])

The measured total cross section is shown in Figure 4 (b) as a function of the beam energy, together with other measurements from photoproduction experiments and compared to the theoretical models. We find that our data do not favor either pure two- or three hard gluon exchanges separately. Instead, a combination of the two processes is required to fit the data adequately. The narrow LHCb states, $P_c^+(4312)$, $P_c^+(4440)$, and $P_c^+(4457)$, produced in the $s$-channel, would appear as structures at $E_\gamma = 9.44, 10.04$ and 10.12 GeV in the cross-section. The results seen in Figure 4 (b) show no evidence for such structures. Thus we conclude that the cross section of $P_c^+$ production is small in photoproduction. We obtain a model-dependent upper limit at 90% confidence level of 4.6%, 2.3%, and 3.8% for $P_c^+(4312)$, $P_c^+(4440)$, and $P_c^+(4457)$, respectively.

5. Hybrid Meson Photoproduction Search

One of the potential candidates for the $1^- -$ hybrid mesons is the $Y(2175)$. It is often referred to as the strangeonium counterpart of the $Y(4260)$ in the charmonium sector, which has been already observed in positron-electron experiments [6, 7]. The GlueX experiment offers a new opportunity to search for this state for the first time in photoproduction. Since the $Y(2175)$ has been seen in $\phi(1020)f_0(980)$ and $\phi(1020)\pi^+\pi^-$ states, we study the exclusive reaction $\gamma p \rightarrow p\pi^+\pi^- K^+K^-$. In order to remove the background underneath the $\phi(1020)$ in the $K^+K^-$ invariant mass spectrum, we fit a $\phi(1020)$ signal plus background as a function of the $\pi^+\pi^-$ invariant mass. In this way, we extract the $\phi(1020)$ yields as a function of the $\pi^+\pi^-$
invariant mass, at different beam energy (Figure 5) and momentum transfer bins (Figure 6). The contribution from $\rho(770)$ is significant. Furthermore an enhancement near the nominal $f_0(980)$ mass is seen, however not significant to claim the evidence. A similar method will be applied to extract the $\phi(1020)\pi^+\pi^-$ invariant mass-dependent $\phi(1020)$ yields in different bins, to search for the $Y(2175)$ state.

**Figure 5.** $\phi(1020)$ yield versus $\pi^+\pi^-$ invariant mass in 3 different bins of beam energy ($E_\gamma$).

**Figure 6.** $\phi(1020)$ yield versus $\pi^+\pi^-$ invariant mass in 3 different bins of momentum transfer ($-t$).

6. Summary
The first part of the GlueX program is to map the conventional meson spectrum, and understand the production mechanisms. Production of the pseudoscalars $\pi^0$ and $\eta$ is dominated by vector meson exchange. The same exchanges are expected to dominate in the production of $1^{-+}$ exotic hybrid mesons. A feasibility study of charmonium production at threshold lead to upper limits of several percent on the branching fraction of the LHCb $P_c^+$ pentaquarks. A Cherenkov detector is currently being installed for hadron identification, which will open a broader program to search for hybrid mesons with strangeness.

References
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