GlueX Capabilities for Nuclear Photoproduction

A. Somov, Jefferson Lab

Nuclear Photoproduction with GlueX
April 28 – 29, 2016
Physics Topics with Nuclear Targets Considered for GlueX

- Photoproduction of vector mesons off nuclei
- Study in-medium modification effects
- Color transparency
- Primakoff production
- Heavy meson photoproduction (open charm, $J/\psi$)
Photon Flux and Run Conditions

Main factors limiting luminosity:

- rate of coincidental hits in tagger (for small beam energies)
- background (neutrons) in the experimental Hall-D

GlueX beam requirements for runs with the LH2 target

- $5 \times 10^7 \gamma/sec$ on target in the energy range $8.4 \text{ GeV} < E < 9.1 \text{ GeV}$
- coincidental rate in the tagger: 15% in a 2 ns time window (500 MH RF)
- collimator diameter: 3.4 mm (transmission factor $\sim 1/6$ for $E_{\text{min}} < E < 12 \text{ GeV}$)
- LH2 target thickness $\sim 3.4 \%$ R.L.
Nuclear targets (no beam polarization)

- Some physics topics require measurements in a larger beam energy range

- Increase size of the collimator to $\geq 5$ mm (transmission factor $\sim 1/3$)

- Increase target thickness to 7 – 10 % R.L.

- Reduce electron beam current by a factor of 9

- Flux of collimated and tagged photons:
  $$2.1 \times 10^7 \, \gamma/\text{sec} \quad (6.5 \text{ GeV} < E_\gamma < 12 \text{ GeV})$$

- Coincidental rate in tagger $\sim 17 \%$
Reconstruction of $\omega \rightarrow e^+ e^-$

- Study reconstruction efficiency of $\omega$-mesons $\gamma p$ interactions (Pythia)
- Relatively good reconstruction efficiency over large $\omega$ momentum range
- Difficult to measure:
  - Small branching fraction $\sim 10^{-4}$, e/\pi separation is critical
- Small cross section: $\sigma (\omega X)_p < 0.8 \text{ Gev/c} \sim 1.8 \text{ nb}$
Reconstruction of $\omega \rightarrow \pi \gamma$

- Production at $E_\gamma = 4$ GeV
Reconstruction of $\omega \rightarrow \pi \gamma$

- Good detection efficiency of $\omega \rightarrow \pi \gamma$ decays at ‘large’ momentum
- Difficult to do line-shape analyses; relatively poor mass resolution $\sigma(m)/m > 3\%$
- Good capability to study nuclear transparency (see Volker M. talk)
Photoproduction of Vector Mesons off Nuclei

• Study interactions of transversely and longitudinally polarized vector mesons with nucleons (Sergey G. talk)

• Measure differential cross section of the vector meson photoproduction in the energy range between 5 GeV and 12 GeV and the momentum transfer range $|t| < 0.5$ GeV$^2$
Nuclear Transparency

E. Chudakov, S, Gevargyan, A, Somov

Input values: \( \sigma_T = 26 \text{ mb} \)
\( \rho_{00} = 0.2 \) (measured by SLAC in photoproduction on nucleon)
$A_{\text{EFF}}$ and $\rho_{00}$ versus $\sigma_L$
Yield of $\omega$ Mesons

- Thickness of nuclei targets – 7% $X_0$

- Production rate of omega mesons in incoherent process on a Al target:

  $$ R = 1.8 \, \omega/sec \quad 6.5 \text{ GeV} < E_\gamma < 7.5 \text{ GeV} \quad 0.07 \text{ reconstructed } \omega / \text{sec} $$

<table>
<thead>
<tr>
<th>Target</th>
<th>$\sigma_{\text{INCOH}} , (\mu b)$</th>
<th>Reconstructed $\omega \rightarrow \pi^0 \gamma$ per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>6 GeV 31</td>
<td>6 GeV 19 5672</td>
</tr>
<tr>
<td></td>
<td>9 GeV 19</td>
<td>9 GeV 6336</td>
</tr>
<tr>
<td></td>
<td>6.5 – 7.5 GeV</td>
<td>8 - 9 GeV</td>
</tr>
</tbody>
</table>
Meson Production with Large Momentum Transfer
Meson Photoproduction with Large Momentum Transfer

- Sensitive to color transparency effects

- Study production $A(\gamma, \pi^- p)$ and $A(\gamma, \pi^+ n)$
  $|t| > 3$ GeV$^2$, $\cos(\theta)_{\text{C.M.}} > -0.75$

- Realatively small cross sections but still may be possible to study with GlueX

- Consider production of other mesons ($\rho$, ...) at high-momentum transfer
Kinematics: $\gamma \eta \rightarrow \pi^- p$
Reconstruction with GlueX

- Process signal events through the GlueX Geant simulation
  - Reconstruction efficiency ~ 75 %

- Trigger: select events with back-to-back hits

- Expected yield: 100 p π⁻ reconstructed events per day

<table>
<thead>
<tr>
<th>Energy range (GeV)</th>
<th>6.5 – 7.5</th>
<th>7.5 – 8.5</th>
<th>8.5 - 9.5</th>
<th>9.5 - 10.5</th>
<th>10.5 - 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\gamma \text{Au}}$ (nb)</td>
<td>10.7.1</td>
<td>59.2</td>
<td>36.0</td>
<td>23.5</td>
<td>14.5</td>
</tr>
<tr>
<td>$N_{\gamma}$ ($10^6$)</td>
<td>2.2</td>
<td>3.4</td>
<td>5.6</td>
<td>4.5</td>
<td>6.0</td>
</tr>
<tr>
<td>$N_{p\pi}$ per day</td>
<td>(29.7)</td>
<td>25.8</td>
<td>23.1</td>
<td>13.7</td>
<td>11.2</td>
</tr>
</tbody>
</table>
Reconstruction with GlueX

- Started studying background in $\gamma n$ interactions using Pythia
  - expected background is small (work in progress):
    binary reaction, two back-to-back tracks

- Study background using $\gamma A$ event generator

- $\gamma p \rightarrow \pi^+ n$ is more difficult to measure (see Or and Werner talks):
  need to trigger on high-$p_T$ pion
  can use time-of-flight wall for the trigger
Summary

- The GlueX detector design was optimized for search and mapping the spectrum of light exotic mesons using the high-intensity linearly polarized photon beam.
  - The detector is designed to have excellent acceptance for both charged particles and photons in the final state.
  - Nuclear production can be studied in the wide photon beam energy range.

- We have started developing physics program for the GlueX to study photoproduction on nuclear targets. Some topics we have considered so far:
  - Photoproduction of vector mesons off nuclei
  - Study in-medium modification effects
  - Color transparency

- We want to get interested people involved and build a strong physics motivation for the experiment.
12 GeV CEBAF Energy Upgrade

- Upgrade CEBAF energy from 6 GeV to 12 GeV.
- New experimental Hall D
  - photon beam (linear polarization)
## Hall D Physics Program

<table>
<thead>
<tr>
<th>Experiment Proposal</th>
<th>Name</th>
<th>Days</th>
<th>Status</th>
<th>Cond.</th>
<th>Target</th>
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</thead>
<tbody>
<tr>
<td>E12-06-102</td>
<td>Mapping the Spectrum of Light Quark Mesons and Gluonic Excitations with Linearly Polarized Photons</td>
<td>120</td>
<td>A</td>
<td></td>
<td>LH₂</td>
</tr>
<tr>
<td>E12-12-002</td>
<td>A study of meson and baryon decays to strange final states with GlueX in HallD</td>
<td>220</td>
<td>A</td>
<td>L3 trigger PID</td>
<td>LH₂</td>
</tr>
<tr>
<td>E12-13-003</td>
<td>A Precision Measurement of the Radiative Decay Width via the Primakoff Effect</td>
<td>79</td>
<td>A-</td>
<td></td>
<td>LHe₄</td>
</tr>
<tr>
<td>E12-13-003</td>
<td>Measuring the Charged Pion Polarizability in the $\gamma\gamma \rightarrow \pi^+\pi^-$ Reaction</td>
<td>25</td>
<td>A-</td>
<td></td>
<td>Sn</td>
</tr>
<tr>
<td>C12-14-004</td>
<td>Eta Decays with Emphasis on Rare Neutral Modes: The JLab Eta Factory Experiment (JEF)</td>
<td>(130)</td>
<td>C</td>
<td>Upgrade forward calorim.</td>
<td>LH₂</td>
</tr>
<tr>
<td>LOI12-15-001</td>
<td>Physics with secondary $K_L$ beam</td>
<td></td>
<td></td>
<td></td>
<td>LH₂, A</td>
</tr>
<tr>
<td>LOI12-15-006</td>
<td>Production $\omega$ mesons off nuclei</td>
<td></td>
<td></td>
<td></td>
<td>A</td>
</tr>
</tbody>
</table>
### Photon Beam Requirements

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Photon Energy Range (GeV)</th>
<th>Polarization</th>
<th>Photon Flux $\gamma$/ sec</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GlueX</strong></td>
<td>8.4 – 9.0</td>
<td>44 %</td>
<td>$5 \cdot 10^7$</td>
</tr>
<tr>
<td>Search for gluonic excitations in the spectra of light mesons</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PrimEx</strong></td>
<td>10.5 – 11.7</td>
<td>None</td>
<td>$7.6 \cdot 10^6$</td>
</tr>
<tr>
<td>A precision measurement of the $\eta \rightarrow \gamma \gamma$ decay width via the Primakoff effect</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Measuring the charged pion polarizability</strong></td>
<td>5.5 – 6.0</td>
<td>76 %</td>
<td>$10^7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Beam photons are produced by 12 GeV electrons (I < 2.2 μA) on a thick diamond crystal (20 μm).

Photon energy: detect bremsstrahlung electrons $\Delta E / E < 0.005$

Pass beam photons through the collimator
- increase the fraction of linearly polarized photons
- beam intensity: $10^8 \gamma$/sec for $8.4 < E_\gamma < 9.1$ GeV

Polarized Photon Beam

- Coherent Bremsstrahlung photon beam
- Photon Spectrum
- 40% polarization
GlueX Detector

**Tracking:**
- Central Drift Chamber
- Forward Drift Chamber

**Calorimetry:**
- Barrel Calorimeter
- Forward Calorimeter

**PID:**
- Time of Flight wall
- Start Counter
- Barrel Calorimeter
Tracking

Central Drift Chamber

- Angular coverage $6^\circ < \theta < 155^\circ$
- 12 axial layers, 16 stereo layers
- 3522 straw tubes (1.6 cm diameter)
- $\text{dE}/\text{dx}$ for $p$, $\pi$ identification
- $\sigma_\phi \sim 150 \, \mu\text{m}$, $\sigma_z \sim 2 \, \text{mm}$

Forward Drift Chamber

- Angular coverage $1^\circ < \theta < 30^\circ$
- 4 packages, 6 cathode/wire/cathode chambers in each package
- $\sim12000$ channels
- $\sigma_{xy} \sim 200 \, \mu\text{m}$

Tracking performance: $\sigma_p / p \sim 1 - 3 \%$
Calorimetry

Forward Calorimeter:
- Angular coverage $2^\circ < \theta < 11^\circ$
- 2800 Pb-glass blocks: 4cm x 4 cm x 45 cm
- $\sigma_{E/E} = 6\% / \sqrt{E} \oplus 2.0\%$
- $\sigma_{xy} = 6.4\ mm / \sqrt{E}$

Barrel Calorimeter:
- Angular coverage $11^\circ < \theta < 120^\circ$
- 191 layers Pb:ScFib:Glue (37:49:14%)
- Double side readout (SiPM)
- $\sigma_{E/E} = 6\% / \sqrt{E} \oplus 1.6\%$
- $\sigma_Z = 5\ mm / \sqrt{E}$
- $\sigma_t = 74\ ps / \sqrt{E} \oplus 33\ ps$
GlueX Commissioning

12 GeV photons delivered to Hall D in the Fall 2015

**12 GeV endpoint**

**Beam energy (GeV)**

\[ \gamma p \rightarrow \gamma \gamma p \]

\[ \pi^0 \rightarrow \gamma \gamma \]

\[ \eta \rightarrow \gamma \gamma \]

\[ \omega \rightarrow \pi^+ \pi^- \pi^0 \]

\[ \rho^0 \rightarrow \pi^+ \pi^- \]

Events / 20 MeV/c^2

Events / 8 MeV/c^2

Events / 16 MeV/c^2

\[ \gamma \gamma \) Invariant Mass [GeV/c^2] \]

\[ \pi^+ \pi^- \pi^0 \) Invariant Mass [GeV/c^2] \]
Experiments using Primakoff Production
Measurement of $\Gamma(\eta \rightarrow \gamma\gamma)$ via Primakoff Effect

**Physics:**
- Light quark mass ratio
- $\eta - \eta'$ mixing angle

$$\Gamma(\eta \rightarrow 3\pi) \propto |A|^2 \propto Q^4$$

$$Q^2 = \frac{m_c^2 - m_s^2}{m_d^2 - m_u^2}, \quad \text{where} \quad \hat{m} = \frac{1}{2}(m_u + m_d)$$

**Measurements:**
- Primakoff $\theta < 0.5^\circ$
- Fit to $\frac{d\sigma}{d\Omega}(\theta)$

- 11.0 - 11.7 GeV incoherent tagged photons
- 30 cm LH$_2$ and LHe$_4$ targets (~3.6% r.l.)
- Forward Calorimeter (FCAL) for $\eta \rightarrow \gamma\gamma$
Nuclear Targets in PrimEX I Experiment

- Experiment performed in Hall-B using a 6 GeV photon beam
- Measure \( \Gamma(\pi^0 \rightarrow \gamma \gamma) \) using nuclear targets: \(^{12}\)C and \(^{208}\)Pb

\[
\gamma + ^{12}\text{C} \rightarrow \pi^0 + ^{12}\text{C} \\
E_\gamma = 4.9 - 5.5 \text{ GeV}
\]

\[
\gamma + ^{208}\text{Pb} \rightarrow \pi^0 + ^{208}\text{Pb} \\
E_\gamma = 4.9 - 5.5 \text{ GeV}
\]
Charged Pion Polarizability

- Use Primakoff production $\gamma A \rightarrow \pi^+ \pi^- A$ to extract pion polarizability - test $\chi_{PT}$ predictions
- Photon energy of interest 5.5 – 6 GeV, polarization 76 %
- Major background from rho decays and $\mu^+\mu^-$
- Requires new muon detector
Quark Distributions in Polarized Mesons

Distribution of valence quarks


Light cone wave function for $\rho$ mesons
J. Forshaw and R. Sandapen

Dipole model of strong interaction

Different distributions of quarks in the transversely and longitudinally polarized mesons
Photoproduction of $\omega$-mesons off Nuclei

Coherent photoproduction $\gamma + A \rightarrow \omega + A$

- obtain the total cross section of transversely polarized $\omega$ meson with nucleons $\sigma_T (\omega N)$
- measure the $\omega$ - photon coupling constant

Incoherent photoproduction $\gamma + A \rightarrow \omega + A'$

- extract the total cross section of longitudinally polarized $\omega$ meson with nucleons $\sigma_L (\omega N)$ which has not yet been measured
- measure nuclear transparency and the spin density matrix elements for different nuclei
Coherent Production of $\omega$-mesons

- Exchange of particle with isotopic spin one (pion exchange) has different signs in photoproduction on proton and neutron
  - the contribution of pion exchange cancels out when amplitudes are summed

- S-channel helicity conservation in production at small angles
  - transversely polarized $\omega$ mesons

\[
\frac{d\sigma_A(q)}{dt} = |F_A(q_\perp, q_L, \sigma_T)| \frac{d\sigma_N}{dt} \bigg|_{t=0}
\]

Obtain $\omega$-photon coupling constant

\[
\frac{d\sigma_N}{dt} \bigg|_{t=0} = \frac{4\pi \alpha}{\gamma_\omega^2 64\pi} \sigma_\omega^2 (1 + \alpha_\omega^2)
\]

Measure coupling constant in photoproduction on nucleons using linearly polarized photons (distinguish contributions from the natural and unnatural parity exchange)

- measure photoproduction cross section on both nuclei and nucleons
- help to sort out some contradictions in the measurements of the $\omega$-photon coupling constant
Incoherent production of $\omega$ mesons

Nuclear transparency

\[
\frac{d\sigma_A(q)}{dt} = \frac{d\sigma_0(q)}{dt} \cdot \left( \rho_{00} N(\sigma_L) + (1 - \rho_{00}) N(\sigma_T) \right)
\]

\[
N(\sigma) = \int \frac{1 - \exp(-\sigma \int \rho(b,z)dz)}{\sigma} d^2b
\]

\[
A_{EFF} = \frac{d\sigma_A(q)}{dt} / \frac{d\sigma_0(q)}{dt}
\]

Spin density matrix elements

\[
\rho_{00}^A = \frac{N(\sigma_L)}{\rho_{00} N(\sigma_L) + (1 - \rho_{00}) N(\sigma_T)} \rho_{00}
\]

Extend the model by taking into account interference of production amplitudes

- required to describe electroproduction of vector mesons

- energy dependent transparency: $N(\sigma_T) \rightarrow W(q_L, \sigma_T)$,
  where $q_L = m^2 / 2E$
Spin Density Matrix Elements

\[ \rho_{00} \]

\[ \sigma_L = 13 \text{ mb} \]

No interference

\[ \rho(0) \]

\[ \rho(\infty) \]

\[ E_\gamma = 9 \text{ GeV} \]

\[ E_\gamma = 5 \text{ GeV} \]

\[ \text{Al, Cu, Ag, Ta, Pb} \]

\[ A \]

\[ 50, 100, 150, 200 \]
Reconstruction of $\omega$-mesons with GlueX

- $\omega$ - mesons reconstructed with GlueX
- Detector calibration is in progress

![Graphs showing $M(3\gamma)$ and $M(\pi^+\pi^-\pi^0)$](image_url)
Medium Modifications of Mesons

- Study modifications of meson properties by nuclear matter:
  - Spectroscopy of hadron line shapes
  - Attenuation measurements

- Use vector mesons to study the mass distribution and medium absorption
  \( c_\tau = 1.3 \text{ fm, } 23 \text{ fm, and } 46 \text{ fm for } \rho, \omega, \text{ and } \phi \)

- In-medium modification measurements have been performed by several experiments
  - Experimental measurements are not completely understood
    (more measurements are required)
## Experimental Results on In-medium Modifications

*S. Leupold, V. Metag, U. Mosel
Int. J. Mod. Phys. E 19 (2010)*

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam GeV</th>
<th>P range GeV/c</th>
<th>$\rho$</th>
<th>$\omega$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring 8</td>
<td>$\gamma A$</td>
<td>1.5 – 2.4</td>
<td>$p &gt; 1$</td>
<td>K$^+$$K^-$ final state</td>
<td>$\Delta \Gamma \sim 70$ MeV $p = 1.8$ GeV/c</td>
</tr>
<tr>
<td>CBELSA/TAPS</td>
<td>$\gamma A$</td>
<td>0.9 – 2.2</td>
<td>$p &gt; 0$</td>
<td>$\pi^0\gamma$ final state</td>
<td>$\Delta \Gamma \sim 130$ MeV $p = 1.1$ GeV/c</td>
</tr>
<tr>
<td>CLAS E01-112</td>
<td>$\gamma A$</td>
<td>0.6 – 3.8</td>
<td>$p &gt; 0.8$</td>
<td>e$^+$$e^-$ final state</td>
<td>$\Delta m \sim 0$ $\Delta \Gamma \sim 70$ MeV $p = 1.1$ GeV/c</td>
</tr>
<tr>
<td>KEK-E325</td>
<td>p $A$ 12</td>
<td>p $&gt; 0.6$ e$^+$$e^-$ final state</td>
<td>$\Delta m /m = -9%$ $\Delta \Gamma \sim 0$</td>
<td>$\Delta m /m = -9%$ $\Delta \Gamma \sim 0$</td>
<td>$\Delta m /m = -3.4%$ $\Delta \Gamma / \Gamma = 3.6$</td>
</tr>
<tr>
<td>GlueX</td>
<td>$\gamma A$</td>
<td>6 – 12</td>
<td>$\pi\pi$ (e$^+$$e^-$)</td>
<td>$\pi^0\gamma$, $\pi^+$$\pi^-\pi^0$, (e$^+$$e^-$)</td>
<td>K$^+$$K^-$ (e$^+$$e^-$)</td>
</tr>
</tbody>
</table>
Transparency $T_A = \sigma_A / A \sigma_N$

Large absorption observed for $\omega$ mesons

not consistent with CBELSA/TAPS results

- Interference between $\omega$ and $\rho$ mesons in the $e^+e^-$ decay mode (?)
GlueX Perspectives to Measure In-medium Effects

- Study medium modifications of light mesons $\rho$, $\omega$, and $\phi$

- Reconstruct mesons in different final states
  
  - study contribution from final state interactions
  
  - small final state distortion in the dilepton final state
    - small branching fractions of $10^{-4} – 10^{-5}$
    - $\rho - \omega$ interference
    - have to study GlueX reconstruction capabilities of dileptons

- Study in-medium effects for different beam energies and meson momenta