Modifications of the $D_{33}^{33}$ (1700) resonance in the nuclear medium

Vahe Sokhoyan

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**Motivation**

- **Goal:** Search for in-medium modifications of baryon resonances
- Pronounced in-medium effect: No bump structure in the photoabsorption cross-section measured for $\gamma + A$
- $\rightarrow$ not fully explained in a model-independent way

![Graph showing data points for $\sigma/A$ vs. $E_\gamma$]  

*Open symbols: $\gamma + p$*  

*Full symbols: $\gamma + A$*  

In-medium modifications

- The width for $\Delta(1232)$ is changed in the nuclear medium from 100 MeV to ~190 MeV in good agreement with the BUU model (University Gießen) calculations.

![Graph showing in-medium modifications](image)

- Second resonance region: No strong experimental indication for significant modifications of $D_{13}(1520)$ or $S_{11}(1535)$.

B. Krusche, Progress in Particle and Nuclear Physics 55 (2005) 46–70
\( \pi^0 \eta \) photoproduction (proton target)

- The production of \( \pi^0 \eta \) pairs best suited to study the \( D_{33} (1700) \) resonance.
- \( \eta \) acts as an isospin filter: Access to \( \gamma p \rightarrow D_{33} (1700) \rightarrow \Delta(1232)\eta \rightarrow p\pi^0\eta \)

\( D_{33} (1700) \) dominates close to the production threshold.

Angular distributions (proton target)

Angular distributions: Reasonable agreement with a model including only the $D_{33}^{\pi}$ amplitude

Polarization observables

Double meson final states:
For a complete experiment, 15 observables are needed!

Polarized cross-section (only polarized beam):
\[
\frac{d\sigma}{dx_i} = \left( \frac{d\sigma}{dx_i} \right)_0 (1 + P_\gamma I^\circ + \delta_l (I^e \cos 2\varphi + I^s \sin 2\varphi))
\]

\(P_\gamma\): degree of circular polarization, \(\delta_l\): degree of linear polarization

Linear polarization: high sensitivity to resonances

- Relatively low polarization at energies ~1 GeV
- Difficulties in extraction of unpolarized cross-sections
Polarization observables

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Polarized cross-section (only polarized beam):

$$\frac{d\sigma}{dx_i} = \left(\frac{d\sigma}{dx_i}\right)_0 (1 + P_{\gamma} I^\circ + \delta_l (I^c\cos 2\varphi + I^s\sin 2\varphi))$$

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Linear polarization: high sensitivity to resonances


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Circular polarization: high sensitivity to $D_{33}^{(1700)}$


High values of polarization achievable at ~1 GeV

No modification of the incoming photon energy spectrum
Measurement of $I^s$ and $I^c$

\[
\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left\{ 1 + \delta_l \left[ I^s \sin(2\phi) + I^c \cos(2\phi) \right] \right\}
\]

\[
I^c(\Phi^*) = I^c(2\pi - \Phi^*)
\]

\[
I^s(\Phi^*) = -I^s(2\pi - \Phi^*)
\]

\[
f(\phi) = A(1 + \delta_l (B\sin2\phi + C\cos2\phi))
\]

![Graph showing the measurement of $I^s$ and $I^c$](image)

\[
I^c = -0.078 \pm 0.053
\]

\[
I^c = -0.093 \pm 0.054
\]

\[
36^\circ < \Phi^* < 54^\circ
\]

\[
306^\circ < \Phi^* < 324^\circ
\]

\[
\Phi^*[^\circ]
\]

\[
\pi^0 \text{ in the production plane}
\]

\[
I^s
\]

\[
\pi^0 \text{ in the production plane}
\]

\[
I^s(\Phi^* + \pi)
\]

\[
\Phi^*[^\circ]
\]
$\pi^0\eta$ photoproduction (CBELSA/TAPS)

$\pi^0\eta$ photoproduction (CBELSA/TAPS)

$W = 1706 \pm 64$ MeV

$W = 1834 \pm 64$ MeV

$W = 1946 \pm 48$ MeV

Closed symbols:
l$^c(\phi^*)$

Open symbols:
l$^c(2\pi - \phi^*)$

Bars: Systematic error estimate

Curves:
- BnGa-PWA
- Valencia model
  M. Döring, E. Oset, U.-G. Meißner
- Fix isobar model
  A. Fix et al., Phys. Rev. C
  82 (2010) 035207

I^s and I^c in γp → pπ^0π^0 and N(1900)3/2^+ resonance

Dominance of the N(1900)3/2^+ resonance directly seen in the data

Beam helicity asymmetry:

\[ W_c^c(\phi) \sim \sigma^+(\phi) - \sigma^- (\phi) \]

\[ W_c^c (\phi) = \sum_{n=1}^{n_{\text{max}}} A_n \sin n\phi \]

Both unpolarized and polarized data indicate the dominance of the \( D_{33} \) wave at energies \( E_\gamma < 1.2 \text{ GeV} \)

Dotted line: fit with the first 3 terms of the sine expansion (A1, A2, A3)
Solid line: isobar model with 6 resonances
Dashed line: only D33 wave


[A2 Collaboration]
Beam helicity asymmetry (proton target)

$W^c(\phi)$ can be expanded as:

$$W^c(\phi) = \sum_{n=1}^{n_{\text{max}}} A_n \sin n\phi$$

- $A_1$ represents **purely** the contribution of the $D_{33}$ wave
- $A_2$ is sensitive to interference terms
- $A_3$ is negligible

Both unpolarized and polarized data indicate the dominance of the $D_{33}$ wave at energies $E_\gamma < 1.2$ GeV

Coefficients of the sine expansion
Solid line: full model prediction
Dashed line: only the $D_{33}$ amplitude.

Existing data and next steps

Existing data sets:

- The structure in these observables is reasonably described by the $D_{33}^{(1700)}$ resonance within the isobar model for the proton target at $E_{\gamma} < 1.2$ GeV (A. Fix, et al.)
- Any changes of these observables beyond FSI will allow access to the in-medium properties of the $D_{33}^{(1700)}$
- Measurements performed by the A2 Collaboration with proton and deuteron targets will be used as a reference
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This program is aiming for:

- Study modifications of the $D_{33}^{(1700)}$ resonance
- Measurement and interpretation of polarization observables for the investigation of in-medium modifications (and unpolarized cross-sections)
- Better understanding of the Final State Interaction (FSI)
- Understanding of the nature of the $D_{33}^{(1700)}$: Is it dynamically generated?
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We are extracting:

- **Differential cross-sections and beam helicity asymmetry close to the $\pi^0\eta$ production threshold with C, Al and Pb targets**
- Data on $^4$He will be acquired in the near future
Understanding of the FSI

Experimental method:

- Investigation of the FSI with light nuclei (deuteron, helium isotopes)
- Investigation of the coherent component
- Measurements with different targets
- New asymmetry data can be useful for the understanding of the mechanisms of the FSI

and:

- Estimates from the model of A. Fix (includes FSI)
- Interested to obtain calculations from the BUU transport model
Example: Significant reduction of the total cross-section was observed for the deuteron target in several reactions, indicating strong FSI effects, but e.g. for the production of 2 neutral pions, the beam helicity asymmetry is in excellent agreement for the free proton (hydrogen target) and quasi-free proton (deuteron target) data (M. Oberle, B. Krusche et al., Phys. Lett. B721 (2013) 237-243 [A2 Collaboration])

Black: free proton, Blue: quasi-free proton. Red: quasi-free neutrons
MAMI and Crystal Ball experiment

Injector $\Rightarrow$ 3.5 MeV
RTM1 $\Rightarrow$ 14.9 MeV
RTM2 $\Rightarrow$ 180 MeV
RTM3 $\Rightarrow$ 882 MeV
HDSM $\Rightarrow$ 1.6 GeV

- High-Flux, Tagged, Bremsstrahlung Photon Beam: Unpolarized, Linear, and Circular
- Polarized and Unpolarized Targets

$E_\gamma = E_o - E_e$
Crystal Ball/TAPS experiment

**Crystal Ball:**
- 672 NaI Crystals
- 24 Particle Identification Detector Paddles
- 2 Multiwire Proportional Chambers

**TAPS:**
- 366 BaF$_2$ and 72 PbWO$_4$ Crystals
- 384 Veto Detectors
Experimental Setup

- Carbon pipe for positioning targets in the Crystal Ball
- Targets: C, Al, Pb and other parts such as an inserter prepared
- Empty insert for the cryostat built in the KPH Mechanical and Vacuum Workshops
Run conditions

- Targets C (2 cm), Al (8 mm), Pb (0.5 mm), empty target
- \(E_{\text{beam}} = 1557\ \text{MeV} \) (+ 8 hours with 883 MeV with the Pb target)
- Circularly polarized photons (electron polarization 70-74%)
- Tagged photon energy \(E_{\gamma} > 500\ \text{MeV}\) for C and Al, \(E_{\gamma} > 780\ \text{MeV}\) for Pb
- Currents: 4.5 nA (C), 7.5 nA (Al), 16.5 nA (Pb)
- Collimator: 2.5 mm
- Trigger: M2+ and
  \[\text{CB}_{E_{\text{sum}}} > 320\ \text{MeV}\] for Al and Pb targets
  \[\text{CB}_{E_{\text{sum}}} > 350\ \text{MeV}\] for C target
Acquired data

- C target ~90 h with 1557 MeV beam
- Al target ~120 h with 1557 MeV beam
- Pb target ~100 h (1557 MeV beam), ~8 h with 883 MeV beam
- Empty ~20 h with 1557 MeV beam
Acquired data

- C target ~90 h with 1557 MeV beam
- Al target ~120 h with 1557 MeV beam
- Pb target ~100 h (1557 MeV beam), ~8 h with 883 MeV beam
- Empty ~20 h with 1557 MeV beam

Preliminary selection of events with $\pi^0\eta$ and $\pi^0\pi^0$ production

- $E_{\gamma_{\text{beam}}} = 1000 - 1450$ MeV
- Selecting events with 4 $\gamma$ (+ 1 charged hit or + X hits)
- Invariant mass cut
- Missing mass cut (?)
- Subtraction of random timing background
- Negligible empty target contribution
Example Spectra (Carbon target)

$E_\gamma = 1100 - 1300 \text{ MeV}$
Example Spectra (Aluminium target)

$E_\gamma = 950 - 1450 \text{ MeV}$

Agreement between “unpolarized” distributions with different helicity

Difference in 3-body kinematics: $\phi$ dependence seen in the data
Very preliminary asymmetries seen in the data for \(~35\%\) of Aluminium data (4 photons + X) events considered

- Curves: red fit to the data, black calculation within isobar model
- Small asymmetry in energy binning → differential distributions
Outlook: Next steps

- New project aiming for the investigation of the $D_{33}^{(1700)}$ resonance in the nuclear medium
- Differential cross-sections for $\pi^0\eta$ photoproduction and beam helicity asymmetry will be extracted
- Existing data obtained with proton and deuteron targets will be used as a reference
- FSI effects will be investigated in cooperation with theory groups

Available manpower:
Master and Diploma students
Experienced postdoc, S. Prakhov (UCLA) will contribute to the data analysis
Thank you for your attention!
Backup
Example Spectra (Carbon target)
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