Photoproduction of Structure in the $d\pi$ System Near the N\Delta Mass: Sign of a Quasi-Bound State?

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Outline /Overview

- Theoretical expectations about two-baryon resonant states

- Experimental observations
  - $\Delta\Delta$ quasi-bound state: WASA/COSY
  - $\pi d$ & pp elastic scattering: SAID analysis

- Photoproduction at CLAS/JLab
  - $\gamma d \rightarrow d \pi^+ \pi^-$ exclusive channel
  - $N\Delta$ quasi-bound state or ISI/FSI?
Two-baryon resonances

- 6 quarks in a bag

- The deuteron
  - 2.2 MeV bound
  - The only clear-cut "dibaryonic molecule"

- Recall the $nn$, $pp$, and $np$ strong spin singlet states are unbound...
  - ... by only ~100 keV
  - One of the great "fine-tuning" mysteries of nature!!
Two-baryon resonances

- **Bound $N\Delta$, $\Delta\Delta$, $\Lambda\Lambda$ (H-particle)**
  - Binding?
  - Width: 'narrow' or 'wide'?
  - Spin, Isospin?

- **Recent WASA@COSY claim of discovery**

- **CLAS study: new observations**

**Diagram:**
- $N\Delta$: $I (J^P) = 1 (2^+)$ ("
- $\Delta\Delta$: $I (J^P) = 0 (3^+)$ "D_{03}"
- $N\Lambda$: $I (J^P) = 1 (2^+)$ ("D_{12}"
Some Thresholds

\[ m_{\Delta^+} + m_N = 1232 + 939 = 2171 \text{ MeV} \]
\[ m_d^+ + m_\pi = 1875 + 140 = 2015 \text{ MeV} \]
\[ m_{\Delta^+} + m_\Delta = 2 \times 1232 = 2464 \text{ MeV} \]

The decay of \( N\Delta \) to \( d\pi \) liberates about 156 MeV at the centroid of the (quasi-) bound state.

For comparison: 
\[ m_{\Delta^+} + m_\Delta = 2 \times 1232 = 2464 \text{ MeV} \]
Theoretical Expectations

- “Y=2 states in SU(6) theory”
  - F. Dyson & N. Xuong, PRL (1964)
  - I=1 J=2 state and I=2 J=1 state in 27 multiplet
- “Multi-quark states Q^6 dibaryon resonances”
  - Bag model: NΔ state in a 5S_2 configuration decaying to the 1D_2 NN partial wave channel
- “Flavor octet dibaryons in the quark model”
  - M. Oka, PRD (1988)
  - One-gluon exchange color magnetic interaction leads to certain strange dibaryons
Theoretical Expectations

- “$NN$ core interactions…from 1 gluon exchange”
  - T. Barnes, S. Capstick, M.D. Kovarik, E.S. Swanson, PRC (1983)
  - OGE and quark-exchange model
  - Deuteron and $N\Delta$ states not found, but “molecular” (weakly bound) $\Delta\Delta$ was found

- “Deeply-bound dibaryon resonances”
  - QCD-like potential model with hyperfine effects
  - $I=0 \ S=3$, well below the $\Delta\Delta \ & \ N\Delta\pi$ thresholds
Theoretical Expectations

- “3-body model calculations of $N\Delta$ and $\Delta\Delta$ dibaryon resonances”
  - $\pi NN$ model with separable pairwise interactions
  - Solve $\pi NN$ and $\pi N\Delta$ Faddeev equations
  - $D_{12} \ N\Delta$ found for $I(J^P) = 1(2^+) & 2(1^+)$
  - $D_{03} \ \Delta\Delta$ found for $I(J^P) = 0(3^+) & 3(0^+)$

Figure 2: Diagrammatic representation of the $\pi NN$ Faddeev equations solved in the present work to calculate $N\Delta$ dibaryon resonance poles.
Quasi-bound states

- Evidence for $\Delta\Delta$ ("$\mathcal{D}_{03}$")
  - WASA-at-COSY experiments (Jülich)

...and numerous others since.
The WASA@COSY result for $\Delta\Delta$ state

- $M \sim 2370$ MeV
- $\Gamma \sim 70$ MeV
- $\Gamma_{\Delta\Delta} < 1/3$ $\Gamma_{\Delta\Delta}$
- $\Delta\Delta$ state interpretation has been disputed*

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...and numerous others since.
WASA@COSY $d^*(2380)$ Resonance

- Evidence for $d^*(2380)$ $D_{03}$ state in $NN \rightarrow d\pi\pi$ in several isospin channels
- SAID Analysis pole position: $2380(10) - i40(5)$ MeV

P. Adlarson et al. (WASA-at-COSY & SAID Data Analysis Center), Phys Rev C 90, 035204 (2014).
A Scenario for $d^*(2380)$ Decay

- Interpretation of WASA/COSY results for reaction $p n \rightarrow d \pi^0 \pi^0$
- Interference mechanism in $d^*$ decay:
  - Sequential decay thru $D_{12}$ ($I \ J^P = 1 \ 2^+$) state
    - $D_{03} \rightarrow D_{03} + \pi \rightarrow d + (\pi \pi)_0$
  - $\sigma$ channel ($\pi \pi$ - S wave)
    - $D_{03} \rightarrow d + \sigma \rightarrow d + (\pi \pi)_0$

**FIG. 1.** The leading mechanisms for the reaction $pn \rightarrow d + (\pi \pi)_0$ in the ABC region. The three-momenta in the c.m. frame of two particles are indicated between the respective lines.

A Scenario for $d^*(2380)$ Decay

- Interference in decay of $d^*$ ($I\ J^P = 0\ 3^+$):
  - Sequential decay thru $D_{12}$ ($I\ J^P = 1\ 2^+$) state
    - $D_{03} \rightarrow D_{12} + \pi \rightarrow d + (\pi\pi)_0$
  - $\sigma$ channel ($\pi\pi$ - $s$ wave)
    - $D_{03} \rightarrow d + \sigma \rightarrow d + (\pi\pi)_0$
  - $\sigma$ mass and width small compared to PDG
    - sign of partial chiral symmetry restoration in dense matter?

P. Adlarson (Wasa@COSY) et al., Phys. Rev. Lett. 106, 242202 (2011)
Quasi-bound states

What about $N\Delta$?

- If a $\Delta\Delta$ ("$D_{03}$") state exists, so should $N\Delta$

- Expect $N\Delta$ to have $I^J = 1^+ 2^+$ ("$D_{12}$")
pp Elastic Scattering

- Partial Wave Analysis
- $^{1}D_2$ wave in $pp$ elastic scattering: structure at 2148 – i63 MeV
- Most prominent “resonance pole” seen in SAID analysis
- Textbook exercise: If an $N\Delta$ quasi-bound state exists, it can decay to $pp$ ONLY if $J_{N\Delta}^P = 2^+$

$\pi d \rightarrow \pi d$ Elastic PWA

- $^3P_2$ wave in $\pi d$ elastic scattering is most prominent
- SAID analysis: "resonance-like" behavior in several partial waves

### S-matrix poles for $N\Delta (\mathcal{P}_{12})$

<table>
<thead>
<tr>
<th>Pole Position $\mathcal{P}_{12}$ (MeV)</th>
<th>Model Approach</th>
<th>Ref.</th>
</tr>
</thead>
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Photoproduction Scenario

- Resembles $\pi d$ elastic scattering but with an off-shell pion.
- Suppose it to be dominant at small $-t$.
CLAS Experiment
What can CLAS see?

- Photons on a deuteron target
  - $g_{10}, g_{13}, g_{14}$ data sets
- Spin-1 photon & spin-1 deuteron:
  - $\mathbf{1} + \mathbf{1} \rightarrow \bar{J} = 0, 1, 2$ in $S$ wave, is favorable
- Isospin $I = \{0,1\} + 0 \rightarrow 0, 1$ allowed
- We looked for both $N\Delta$ and $\Delta\Delta$ structures
- $\gamma d \rightarrow p p \pi^-$ - messy mix of partial waves
- $\gamma d \rightarrow d \pi^+ \pi^-$ - coherent exclusive production: clean!
Parametric Monte Carlo

- $\gamma d \rightarrow \{d \pi\} \pi$ - signal channel
- $\gamma d \rightarrow d \rho$ - main background
- $\gamma d \rightarrow d \pi \pi$ - phase space background

Model the run conditions:
- Bremsstrahlung photon beam
- Reverse CLAS torus field
- Assume $t$-channel dominance (slope $2 \text{ GeV}^2$)
Parametric Monte Carlo

$$\gamma d \rightarrow d \pi^+ \pi^-$$

phase space background
Parametric Monte Carlo

\[ \gamma d \rightarrow \{d \pi^\pm\} \pi^\mp \]

signal events
Parametric Monte Carlo

\[ \gamma d \rightarrow d \pi^+ \pi^- \]

\( \rho \) background

\[ M(d\pi^+) \]

\[ M(d\pi^-) \]
Preliminary CLAS data showing:

- No sign of a "ΔΔ" signal
- Evidence for $\rho$ background
- Evidence for a "$N\Delta$" signal
Gash at $W = 2.46 \text{ GeV}/c^2$: known gap in CLAS coverage

No $\Delta\Delta$ visible in CLAS/g13 (maybe not formed in $\gamma d$)

Recall WASA@COSY claims $\Delta\Delta$ at $W = 2.37 \text{ GeV}/c^2$ in $pn \rightarrow d\pi^+\pi^-$

No hint of a “$\Delta\Delta$” bump!

Unnormalized yield

Entries 3176523
$$\gamma d \rightarrow d \rho, \quad \rho \rightarrow \pi^+\pi^-$$ 

background
Dalitz Plot: $d\pi^+ \text{ vs. } d\pi^-$

Acceptance-corrected CLAS (g13) data

$-0.75 < \cos\theta_{\pi^\pm} < 0.94$

$2.45 < W < 3.15 \text{ GeV}$

W~constant on diag.

- Gap at $W=2.45 \text{ GeV}$
  due to missing tagger channel

Clear preference for $d\pi^\pm$ correlation near the $N\Delta$ mass!
Dalitz Plot: $d\pi^+ vs. d\pi^-$

Acceptance-corrected CLAS (g13) data

- $-0.75 < \cos\theta_{\pi^\pm} < 0.94$
- $2.45 < W < 3.15$ GeV
- $W$~constant on diag.
  - Gap at $W=2.45$ GeV due to missing tagger channel
- Clear preference for $d\pi^\pm$ correlation near the N\Delta mass!
Fit to Resonance-like Shapes

- Use narrow data slices in $W = \sqrt{s}$
- Assume a Breit-Wigner line shape
- Let $d\pi$ system decay to $N\Delta$ (L=0), $d\pi$ (L=1), and $NN$ (L=2)
- $\rho$ not cut away; model as P.S. background
- Incoherent amplitudes
- Following fits are prelude to PWA analysis
\[ \gamma d \rightarrow (d\pi) \pi \quad 2.55 < W < 2.60 \text{ GeV} \]

**Non-resonant background**

Data and Fit

- \(0.704 < \cos \Theta_{\pi} < 0.82\)
- \(\chi^2_\nu = 1.53\)

**Preliminary**

Data and Fit

- \(0.75 < \cos \Theta_{\pi} < 0.89\)
- \(\chi^2_\nu = 1.92\)

**Preliminary**
Fit to Resonance-like Shapes

\[
\frac{d\sigma}{dm} \sim \left\{ \frac{1}{p_{\gamma d}^{cm}} \right\} \frac{m_0^2 \Gamma_i \Gamma_f}{(m_0^2 - m^2)^2 + m_0^2 (\Gamma_{L=0}^{N\Delta} + \Gamma_{L=1}^{\pi d} + \Gamma_{L=2}^{pp})^2}
\]

Let the fit "choose" the preferred shape from \(L=0, 1, 2\)

\[
\Gamma_{L=2}^{pp} = \alpha_{pp} \Gamma_0 \left( \frac{q_{pp}}{q_{0_{pp}}} \right)^{2L+1=5} \left( \frac{m}{m_0} \right) (B'_L=q_{0_{pp}}(q, q_0))^2
\]

\[
\Gamma_{L=1}^{\pi d} = \alpha_{\pi d} \Gamma_0 \left( \frac{q_{\pi d}}{q_{0_{\pi d}}} \right)^{2L+1=3} \left( \frac{m}{m_0} \right) (B'_L=q_{0_{\pi d}}(q, q_0))^2 = \Gamma_f \Delta \Gamma_i
\]

\[
\Gamma_{L=0}^{N\Delta} = \alpha_{N\Delta} \Gamma_0 \left( \frac{q_{N\Delta}}{q_{0_{N\Delta}}} \right)^{2L+1=1} \left( \frac{m}{m_0} \right) (B'_L=q_{0_{N\Delta}}(q, q_0))^2 \xrightarrow{\text{Non-relativistic}} \alpha_{N\Delta} \Gamma_0 \left( \frac{m}{m_0} \right)
\]
Evidently, $m_{\text{Peak}} < m_{N\Delta}$

$$\gamma d \rightarrow (d\pi)\pi \quad 2.60 < W < 2.65 \text{ GeV}$$

**Mass (GeV)**

**Data and Fit**

- $0.736 < \cos\theta_{\pi} < 0.82$
- $\chi^2 = 1.56$

**Preliminary**

**Mass (GeV)**

**Data and Fit**

- $0.742 < \cos\theta_{\pi} < 0.792$
- $\chi^2 = 1.02$

**Preliminary**
$\gamma d \rightarrow (d\pi) \pi \quad 2.65 < W < 2.70 \text{ GeV}$

Evidently,

$m_{\text{Peak}} < m_{N\Delta}$
Evidently, $m_{\text{Peak}} < m_{N\Delta}$.

\[ \gamma d \rightarrow (d\pi)\pi \quad 2.70 < W < 2.75 \text{ GeV} \]
Observations

- Peaks are all below the $N\Delta$ centroid, but widths are not identical: $\cos \theta_\pi$ dependent
- Very preliminary result:
  - $m_{\text{peak}} = 2115 \pm 10$ MeV/c$^2$
  - FWHM = $125 \pm 25$ MeV
- We have remaining acceptance issues near high and low edges
- Fits "choose" non-relativistic BW line shapes with $\Gamma_{\pi d}^{L=1} \Delta = \Gamma_i$ numerator only few %
  - $L = 1, 2$ decay branches denominator
Summary/Conclusion

- Big $\pi^\pm d$ signal seen in CLAS photo-production data, peaking below the $N\Delta$ mass.
  - Strongest at forward pion angle.

- Resonance mass and width depends on line-shape model, $\rho$ treatment, amplitude interferences...

- We are NOT now claiming that this $d\pi$-system bump is necessarily the expected resonant $D_{12}$ state... but it could be. Caveats:
  - Final/initial state interactions, other dynamics...
  - Scattering matrix poles vs. peaks in spectra...
Supplemental slides
Why not Deuteron Breakup?

- Would the system survive on the way to forming an $N\Delta$ State?
  - Fermi motion helps!
- Let $\gamma d \rightarrow NN^*(1520) \rightarrow N\Delta\pi$, $<170$ MeV/c Fermi motion, and let $N^*$ decay along z-axis

1) $\gamma N \rightarrow N^*$ Lab Frame

2) $N^*N$ Lab Frame

3) $N^*(1520)$ Rest Frame

4) $\Delta N$ Lab Frame

5) $\Delta N$ c.m. Frame

Relative Kinetic E $\approx 0.$ MeV
Theory Approaches for $\Delta\Delta$

- Group theory predicts both states $I J^P = 0 \ 3^+ (D_{03} \text{ a.k.a. } d^*)$ and $I J^P = 3 \ 0^+ (D_{30})$

- Hidden-color configurations make both bound, but $D_{03}$ more so:
  - Chiral-quark model
    - 2393 vs. 2440 MeV
  - Quark Delocalization
  - Color Screening Model
    - 2357 vs. 2423 MeV

Theory Approaches for $\Delta\Delta$

- Most exotic interpretation for $d^*$ ($I^J = 0 \, 3^+$): a "hexa-quark" dominated structure

- Chiral Quark Model with Resonating Group Method
  - Mass 2.38 to 2.42 GeV
  - 2/3 hidden color configuration (CC)
  - RMS size 0.76 - 0.88 fm (!)
  - "Narrow" (~70 MeV), since CC component does not break up directly

CLAS Experiment

- **Photoproduction:**
  - Targets: unpolarized LH$_2$, polarized p, & HD-ice
  - Beams: unpolarized, circular, linear, to $\sim$5 GeV
  - Reconstructed $K^+p\pi^-(\pi^0)$ or $K^+\pi^+\pi^- (n)$
  - $20\times10^9$ triggers $\rightarrow 1.41\times10^6$ $KY\pi$ events in $g_{11a}$

- **Electroproduction:**
  - $Q^2$ from $\sim$0.5 to $\sim$3 (GeV/c)$^2$
  - Structure functions from Rosenbluth and beam-helicity separations