Searching for $d^*$ Dibaryons with CLAS

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Working with:
Reinhard Schumacher, Carnegie Mellon University
Dibaryon Resonance Theory

* Spin-flavor SU(6)†:
  †F. Dyson and N. Xuong, Phys. Rev. Lett. 13 815 (1964).
  * Predict multiplets for NΔ, ΔΔ states

* Bag model†:

* QCD-like potential model†:

* Quark model†:

* 1-gluon exchange†:
Dibaryon Resonance Theory

* 3-body hadronic models & Faddeev equations†:
  * $\pi NN, \pi N\Delta$ channels: $N\Delta, \Delta\Delta$ bound below threshold

* QCD sum rule study of $d^*(2380)$ †:
  * 6-quark interpolating currents, $\Delta\Delta$-like operators

* Intermediate dibaryons in $\pi$ production in NN†:
  * Relativistic helicity amplitudes: ONE & intermediate $N\Delta$

* Meson assisted dibaryons†:
  * Enhance binding of $L = 0 BB'$ through strong $\pi B, \pi B'$ attractions
SAID Dibaryon Evidence

  * Resonance like-structures: $^1D_2, ^3F_3, ^3P_2 - ^3F_2, ^3F_4 - ^3H_4$

  * Argand plot: Strong $^1D_2P, ^3F_3D, ^1G_4F$ resonance-like structures

* $\pi^+d \rightarrow \pi^+d$ (R. A. Arndt, et al., Phys. Rev. C 50, 1796 (1994)):
  * Argand plot: Strong $^3P_2, ^3D_3, ^3F_4$ resonance-like structures

FIG. 7. Argand plot of the dominant $\pi d$ partial-wave amplitudes $^3P_2, ^3D_3$, and $^3F_4$ which correspond to the $^1D_2, ^3F_3$, and $^1G_4$ pp states, respectively. (Compare Fig. 7 of Ref. [3]). The X points denote 50 MeV steps. All amplitudes have been multiplied by a factor of $10^3$. 

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WASA-at-COSY $d^*(2380)$

* Evidence for $d^*(2380)$ $\Delta \Delta$ state in $pN \rightarrow d\pi\pi$


CLAS g13 d* Searches
CLAS g13 Experiment

* JLab CEBAF accelerator: e⁻ beam, 6 GeV era
* g13 experiment: 2006 – 2007, LD₂ target
  * Analysis: Eₑ⁻ = 2.655, 1.990 GeV
  * γ beam: Radiator, γ tagger detects e⁻
* Hall-B CLAS-6 detector†: 6 sectors
  * DC: Tracking, ST & TOF: Timing

†B. A. Mecking et al. (CLAS), Nucl. Instr. and Meth. A 503, 513 (2003)
Deuteron ID

* Can reconstruct deuterons with CLAS
Missing Mass Squared

* Virtually no background
* Scale normalized by peak height

\[ \gamma d \rightarrow d \pi^+ \pi^- \ \text{Missing Mass Squared (GeV/c}^2)^2 \]
$d \pi^+ \pi^- -$ Invariant Mass

* Raw $d \pi^+ \pi^-$ yields: Not acceptance-corrected
  * Gash at $W = 2.46$ GeV/$c^2$: Bad tagger counter
* WASA-at-COSY: $\Delta \Delta$ at $W = 2.37$ GeV/$c^2$ in $pn \rightarrow d \pi^+ \pi^-$
* No obvious $\Delta \Delta$ visible in g13: Maybe PWA, or not in $\gamma d$

![CLAS Raw Yield](image1)

![WASA](image2)
Dalitz Plot: $d\pi^+ \text{ vs. } d\pi^-$

- Raw yields, All $W$
- Gash: Bad tagger counter ($W = 2.46 \text{ GeV/c}^2$)
Dalitz Plot: $d \pi^+ \text{ vs. } d \pi^-$

* Raw yield 1D slices: $d \pi$ peaks dominate
\[ \gamma d \rightarrow d \rho, \quad \rho \rightarrow \pi^+ \pi^- \]

* Raw yield: \(\rho\) dominates at high W, long tail

W-granularity: \(\gamma\)-beam tagger detector
Deuteron Breakup?

* Would deuteron break-up trying to form $N\Delta$?
* Deuteron binding energy is 2.225 MeV
* Not necessarily: Fermi motion
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1) $\gamma N \rightarrow N^*$
   (Lab Frame)
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3) $N^*(1520)$ Rest Frame
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3) $N^*(1520)$ Rest Frame

4) $\Delta N$ Lab Frame
   Relative Kinetic E $\approx 0.25$ MeV
Dalitz Plot W-Bins

* W-bins are thin: kinematics (d is heavy), 500 MeV/c d min-p cut

Non-physical events: Likely wrong beam $\gamma$

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Simple Fits to the Data

* Fit acceptance-corrected data in narrow bins of $W$
* Fit $d\pi$ mass to Breit-Wigner
* Fit $d\pi$ BW decay to:
  * $L = 0$ ($N\Delta$)
  * $L = 1$ ($d\pi$)
  * $L = 2$ (NN)
  * Let fit choose best match
* $\rho$ modeled as phase-space
* Incoherent sum of amplitudes
  * No interference terms
* Prelude: Need full PWA

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Fits by Reinhard Schumacher, CMU
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Breit-Wigner Fit Functions

\* Relativistic $d\pi$ Breit-Wigners in $\gamma d \rightarrow d\pi^+\pi^-$

\* $\alpha$: Fit parameters: Let fit “choose” preferred shape: $L = 0, 1, 2$

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

\[
\Gamma_{pp}^{L=2} = \alpha_{pp} \Gamma_0 \left( \frac{q_{pp}}{q_0^{pp}} \right)^{2L+1=5} \left( \frac{m}{m_0} \right) (B_{L=2}^\prime (q, q_0))^2
\]

\[
\Gamma_{\pi d}^{L=1} = \alpha_{\pi d} \Gamma_0 \left( \frac{q_{\pi d}}{q_0^{\pi d}} \right)^{2L+1=3} \left( \frac{m}{m_0} \right) (B_{L=1}^\prime (q, q_0))^2 = \Gamma_f \cong \Gamma_i
\]

Final-state: $d\pi$

\[
\Gamma_{N\Delta}^{L=0} = \alpha_{N\Delta} \Gamma_0 \left( \frac{q_{N\Delta}}{q_0^{N\Delta}} \right)^{2L+1=1} \left( \frac{m}{m_0} \right) (B_{L=0}^\prime (q, q_0))^2 \xrightarrow{\text{Non-relativistic}} \alpha_{N\Delta} \Gamma_0 \left( \frac{m}{m_0} \right)
\]

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Breit-Wigner Distributions

- Various L: Relativistic $d\pi$ Breit-Wigners (& phase-space factor)

\[ \pi d \text{Breit-Wigners, } m_0 = 2.15 \text{ GeV, } \Gamma_0 = 0.15, W = 2.5 \]
\[ \gamma d \rightarrow (d \pi) \pi, \ 2.55 < W < 2.6 \text{ GeV} \]

Background: \( \rho \), phase-space

**Preliminary**

Data and Fit

\[ 0.704 < \cos \theta_\pi < 0.82 \]

\[ \chi^2_\nu = 1.53 \]

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```
$\gamma d \to (d \pi ) \pi , 2.6 < W < 2.65 \text{ GeV}$

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$\gamma d \rightarrow (d \pi^-) \pi^+, 2.65 < W < 2.7 \, \text{GeV}$

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$\gamma \, d \rightarrow (d \, \pi) \, \pi$, $2.7 < W < 2.75$ GeV

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Fit Observations

∗ Peaks all below the NΔ threshold (possibly a bound-state?)
∗ But widths are $\cos(\theta_\pi)$ dependent
∗ Fits dominantly “choose” $L = 1$
∗ Very preliminary, naïve-fit result (both peaks):
  ∗ $m_{\text{peak}} = 2115 \pm 10$ MeV/$c^2$
  ∗ FWHM = $125 \pm 25$ MeV/$c^2$
Summary & Conclusions
Summary

* 3.1 million ~clean $\gamma d \rightarrow d \pi^+ \pi^-$ events
* No $\Delta \Delta$ observed in $\gamma d \rightarrow d \pi^+ \pi^-$
* Strong $d \pi$ structures seen in $d \pi^+ \pi^-$ Dalitz plot
  * Mass peaks below $N\Delta$ threshold
  * Fits are very simple naïve
* Need full amplitude analysis to determine nature of peaks
  * Dynamically generated?
* Setting up amplitude analysis
  * Covariant helicity-coupling amplitudes
  * Tricky: Three-body final state
Mis-PID Missing Mass

- If deuteron was proton, calculated neutron missing mass

<table>
<thead>
<tr>
<th>MissingNeutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
</tbody>
</table>

- No background from misidentifying the d
Dalitz w/ $\rho$-Cut: $d\pi^+$ vs. $d\pi^-$

* $\rho$ cut removed most background under peaks.
Angular Momentum

* Assume d π structures are bound states of NΔ
* Adding angular momentum: For: \( J \rightarrow j_1, j_2: \ |j_1 - j_2| \leq J \leq j_1 + j_2 \)
* From NΔ:
  * \( L_{N\Delta} \) most likely = 0 (bound state near threshold)
  * \( P_{N\Delta} = P_N P_\Delta (-1)^L \) → \( P_{N\Delta} = +1 \)
  * \( J_{N\Delta} = J_N + J_\Delta + L_{N\Delta} = 1, 2 \) → \( J_{N\Delta} = 1 \) or 2
* From π d:
  * \( P_{\pi d} = P_\pi P_d (-1)^L = P_{N\Delta} = +1 \) → \( L_{\pi d} = 1, 3, 5 \ldots \)
  * \( J_{\pi d} = J_\pi + J_d + L_{\pi d} = J_{N\Delta} = 1 \) or 2 → \( L_{\pi d} = 1 \) or 3
* Thus if the π d bands are NΔ resonances, we expect:
  * \( J^P_{N\Delta} = 1^+ \) or \( 2^+ \), \( L_{\pi d} = 1 \) or 3
* Previous evidence in pp scattering: \( J^P_{N\Delta} = 2^+ \)

<table>
<thead>
<tr>
<th>Particle</th>
<th>( J^P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma )</td>
<td>( 1^- )</td>
</tr>
<tr>
<td>( \pi )</td>
<td>( 0^- )</td>
</tr>
<tr>
<td>( N )</td>
<td>( \frac{1}{2}^+ )</td>
</tr>
<tr>
<td>( \Delta )</td>
<td>( \frac{3}{2}^+ )</td>
</tr>
<tr>
<td>( D )</td>
<td>( 1^+ )</td>
</tr>
</tbody>
</table>
Breit-Wigner Distributions

* Relativistic Breit-Wigner (of particle \((d^*)\)) mass \(m_{d^*}\) and width \(\Gamma(M)\):

\[
BW(M) = \frac{m(d^*)\Gamma(d^*)}{(M^2 - m_{d^*}^2)^2 + m_{d^*}^2 [\Gamma(M)]^2}
\]

Blue: Fit parameters

* \(\Gamma(M)\) is effectively the coupling strength to a given channel

* \(\Gamma(M)\) is not constant: Depends on kinematic constraints:
  * Momentum \((q)\) of final state particle in decay CM frame
  * Orbital angular momentum \(L\) of decay products

\[
\Gamma(M) = \Gamma_{(d^*)} \left( \frac{q}{q_0} \right)^{2L+1} \left( \frac{m(d^*)}{M} \right) [B'_L(q, q_0)]^2
\]

\[
B'_0 = 1
\]

\[
B'_1(q, q_0) = \sqrt{\frac{1 + q_0^2d^2}{1 + q^2d^2}}
\]

\(q_0 = q(m_D)\), \(d\) typically = 1 fm (Radius / Impact Parameter)
Breit-Wigner Distributions

* We want to fit acceptance-corrected yields: \( \propto \frac{d\sigma}{dW} \)

* If reaction: \( A, B \rightarrow X \rightarrow C, D \) then in the CM frame:

\[
\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2} \frac{1}{W^2} \frac{p_C}{p_A} |M|^2, \quad |M|^2 \propto BW(M) \quad \text{See (e.g.) Halzen & Martin}
\]

* Similarly, for: \( A, B \rightarrow C, D \quad D \rightarrow F, G \) (This study) fit to:

\[
\frac{d\sigma}{d\Omega}(M) \propto \frac{1}{W^2} \frac{p_C(W) p_F(M)}{p_A(W)} \frac{m_D \Gamma(M)}{(M^2 - m_D^2)^2 + m_D^2 [\Gamma(M)]^2}
\]

\((p_A \text{ and } p_C \text{ in CM, } p_F \text{ in CM of D})\)

* Where, in general, for \( A \rightarrow B, C \):

\[
p_B(m_A) = \frac{1}{2m_A} \sqrt{\left( m_A^2 - (m_B + m_C)^2 \right) \left( m_A^2 - (m_B - m_C)^2 \right)}
\]

For more details, see (e.g.) PDG + Kei Moriya's thesis.
Breit-Wigner Distributions

* $d \pi$ Breit-Wigners in $\gamma d \rightarrow d \pi^+ \pi^-$ (all with $L = 0$)

$\pi D$ Breit-Wigners with $\mu = 2.15, \Gamma_0 = 0.15, f(\mu) = 1.0$

* $\Gamma(M)$, phase space critical for fitting line shape

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Some Thresholds

\[ m_{\Delta} + m_N = 1232 + 939 = 2171 \text{ MeV} \]

\[ m_d + m_\pi = 1875 + 140 = 2015 \underline{\text{MeV}} \]

\[ m_{\Delta} + m_{\Delta} = 2 \times 1232 = 2464 \text{ MeV} \]

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

For comparison: