Photoproduction of the $d^*(2380)$ Dibaryon

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Overview

- Motivation
- Experimental Setup
- $\Sigma$ Results
- $C_X'$ Preliminary Results
Motivation - Recent Observations

- LHCb has recently observed tetraquark and pentaquark candidate states

![LHCb measurement graph](image)

Figure: [1] - LHCb measurements of the decay $B^+ \rightarrow J/\psi \phi K^+$ indicating four tetraquark candidates

- A $uuuddd$ hexaquark candidate, the $d^*(2380)$, has also been observed by another collaboration

Motivation - $d^*(2380)$ Dibaryon

Figure: [1,2] - Results from WASA-at-COSY showing structure at $\sqrt{s} = 2380$ MeV

- $d^*$ has $J^\pi = 3^+$, $m = 2380$ MeV and $\Gamma = 70$ MeV

- $d^*$ predominantly (90%) decays via $d^* \rightarrow \Delta\Delta$

Motivation - $d^*(2380)$ Dibaryon

$\text{d}^* \text{ evidence in p-n scattering}$

$\text{pn} \rightarrow d^*(2380)$

WASA data

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Motivation - New Degree of Freedom in Neutron Stars?

I. Vidaña, M. Bashkanov, D.P. Watts, A. Pastore, PLB 781, pp112-116, 2018
Motivation - Neutron Stars

- Need to know more about size and internal structure of d*(2380) → Need photoproduction measurements
Motivation - d*(2380) Photoproduction

- One potential photoproduction channel is $\gamma + d \rightarrow d^* \rightarrow p + n$

- Anomalous proton polarisation in d* region?

Motivation - d*(2380) Dibaryon

Figure: [1] - Model predictions of the “size” of the d* (right) compared to deuteron (left)

Motivation - Polarisation Observables

- Can gain information about the state by measuring polarisation observables in the reaction

<table>
<thead>
<tr>
<th>Observable</th>
<th>Helicity Amplitude Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_y$</td>
<td>$2\Im \sum_{i=1}^{3} [F_{i+}^* F_{(i+3)-} + F_{i-} F_{(i+3)+}^*]$</td>
</tr>
<tr>
<td>$T$</td>
<td>$2\Im \sum_{i=1}^{2} \sum_{j=0}^{1} [F_{(i+3j)+}^* F_{(i+3j+1)+} + F_{(i+3j)-} F_{(i+3j+1)-}^*]$</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>$2\Re \sum_{i=1}^{3} (-i)^{i} [-F_{i+} F_{(4-i)-}^* + F_{(3+i)+} F_{(7-i)-}^*]$</td>
</tr>
<tr>
<td>$T_1$</td>
<td>$2\Im \sum_{i=1}^{3} (-i)^{i} [-F_{i+} F_{(4-i)-}^* + F_{(3+i)+} F_{(7-i)-}^*]$</td>
</tr>
<tr>
<td>$C_{x'}$</td>
<td>$2\Re \sum_{i=1}^{3} [F_{i+}^* F_{(i+3)-} + F_{i-} F_{(i+3)+}^*]$</td>
</tr>
<tr>
<td>$C_{z'}$</td>
<td>$\sum_{i=1}^{6} {</td>
</tr>
<tr>
<td>$O_{x'}$</td>
<td>$2\Im \sum_{i=1}^{3} (-i)^{i+1} [F_{i+} F_{(4-i)-}^* + F_{i-} F_{(7-i)-}^*]$</td>
</tr>
<tr>
<td>$O_{z'}$</td>
<td>$2\Im \sum_{i=1}^{3} (-i)^{i+1} [F_{i+} F_{(4-i)-}^* + F_{(3+i)+} F_{(7-i)-}^*]$</td>
</tr>
</tbody>
</table>

- $F$ terms relate to helicity amplitudes
Motivation - New Polarimeter

- $\vec{n}$ previously unmeasured

- Polarimeter can measure $\vec{n}$ and $\vec{p}$ simultaneously

- Measure neutron via charge exchange interactions in polarimeter

- Establish if $d^*(2380)$ dibaryon has Electromagnetic Coupling
  → Tests of size and internal structure
MAMI Layout
A2 Hall Setup

Graphite Polarimeter

PID

MWPC

Polarimeter Support

Y
Overview of Polarimeter Setup

Graphite

Aluminium Support Pipe
- Installed new polarimeter at A2 hall in MAMI

- Real, polarised (circularly and linearly available) photon beam in A2 hall

- \( \sim 640 \) hour run in August 2016

- \( \Sigma, C_{x}', C_{z}', P^B_y, P^n_y, O_{x}', O_{z}' \) measurable

- To measure \( \Sigma \), need to look at angular distribution for events without scattering

- To measure \( C_{x}' \) need to examine angular distribution of scattered neutrons
### Event Selection - Particle Assignment

- Particle assignment is based upon detector hit combinations

<table>
<thead>
<tr>
<th></th>
<th>Proton</th>
<th>Charge Exchange Proton</th>
<th>Neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MWPC</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>CB</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

![Diagram showing particle interactions and detector hits](image)
Event Selection

- Energy loss correction applied to the proton track

- Reconstruct the “neutron” track from proton track information via
  \[ n_{\text{rec}} = (d + \gamma) - p \]

- Cuts:
  - Proton vertex
  - Missing mass of reconstructed track -
    \[ M_n = \sqrt{E_n^2 - p_n^2} \]
  - \( dE_{\text{PID}} \) vs \( E_{\text{CB}} \) cut on proton track (banana cut)
  - Distance Of Closest Approach cut (DOCA)
Event Selection - DOCA Method

$p$ Vertex  $p'$ Vertex

$p$, $p'$, $n$, $Z$ (or $\gamma$)
Event Selection - DOCA

- DOCA occurs at the Point Of Closest Approach (POCA)

\[ r_{POCA} = \sqrt{x_{POCA}^2 + y_{POCA}^2} \]

Component Key
- Target Cell
- PID and Target Cover
- Polarimeter

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$\Sigma$ - Asymmetry Fitting

$\phi_p \ 475 \pm 5\text{MeV CM12}$

\[
\frac{N^\parallel(\phi_p) - N^\perp(\phi_p)}{N^\parallel(\phi_p) + N^\perp(\phi_p)} = P^\text{lin}_\gamma \Sigma \cos(2\phi_p)
\]

<table>
<thead>
<tr>
<th>Sigma_475MeV_CM12_Hist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
</tr>
</tbody>
</table>
Results

Black Data Points from - J.PhysG, 17, 8, 1189, F. V. Adamian et. al.
Results published in - PLB, 789, 7-12, M. Bashkanov, S.Kay, D.P. Watts, C. Mullen et. al.

Previous Results

This Analysis

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Σ Results

![Graph showing the dependence of Σ(ΣOn) on Eγ.]

- This Work
- Adamian91
- Gorbenko82
$C_{\chi'}$ - Asymmetry

\[ \phi_{Sc} \text{ Asymmetry (650 \pm 50) MeV CM3} \]

\[ \frac{N^- (\phi_{p'}) - N^+ (\phi_{p'})}{N^- (\phi_{p'}) + N^+ (\phi_{p'})} = \frac{A_{\text{eff}} P \Phi C_{\chi} \sin \phi_{sc}}{1 + A_{\text{eff}} P \cos \phi_{sc}} \]
$C_{x'} - \text{Results}$
Outlook and Summary

- Event selection identifies clean sample of scattered events

- $\Sigma$ results extracted, consistent with existing data and alternative analysis

- $\Sigma$ results from APLCON analysis published in PLB, PLB 789 pp7-12, https://doi.org/10.1016/j.physletb.2018.12.026

- Initial interpretation of $\Sigma$ results suggests hints of the influence of the $d^*(2380)$

- Preliminary analysis of $C_{x'}$ carried out

- Refinement of analysis ongoing
Thanks for listening, any questions?

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In partnership with the A2 collaboration at MAMI

Financial support for this conference presentation was provided by the Canadian Institute of Nuclear Physics
- **Distance Of Closest Approach** (DOCA) method is used to calculate point where scattering event occurred

- $x_i$ is point of closest approach, $\hat{u}_i$ is initial unit vector of track, $v_i$ is initial vertex, $t_i$ is scalar constant to be determined

\[
x_i = v_i + t_i \hat{u}_i
\]

- DOCA occurs at point where distance between two tracks, $\Delta x$, is minimised

- For this minimisation the following condition must be true

\[
\hat{u}_i \cdot \Delta x = 0
\]
- From this a system of two equations with two unknowns, $t_1$ and $t_2$ can be created with solutions

\[
t_1 = \frac{\Delta v \cdot [\hat{u}_1 - \hat{u}_2 (\hat{u}_1 \cdot \hat{u}_2)]}{(\hat{u}_1 \cdot \hat{u}_2)^2 - 1}
\]

\[
t_2 = \frac{\Delta v \cdot [\hat{u}_1 (\hat{u}_1 \cdot \hat{u}_2) - \hat{u}_2]}{(\hat{u}_1 \cdot \hat{u}_2)^2 - 1}
\]

- This allows an interaction point to be defined, this is the Point Of Closest Approach (POCA)
Event Selection - DOCA

$Z_{POCA}$ vs $r_{POCA}$

- Polarimeter
- Target

Entries 143994
Event Selection - DOCA

XY Vertex Point of Scatter from DOCA Method
Σ Determination

- Can extract Σ by forming the asymmetry

\[
\frac{N^\parallel(\phi_p) - N^\perp(\phi_p)}{N^\parallel(\phi_p) + N^\perp(\phi_p)} = P^{\text{lin}}_{\gamma} \Sigma \cos(2\phi_p)
\]

- i.e. \(\cos(2\phi_m)\) asymmetry of amplitude \(P^{\text{lin}}_{\gamma} \Sigma\) between two linear polarisations

- Note that this is not a recoil observable, can look at pn events with no scattering
Linear Polarisation as a Function of $E_\gamma$

- 1st Coherent Edge
- 2nd Coherent Edge
$\Sigma$ - Interpretation/Analysis

$\Sigma(\cos\theta_{\text{CM}}) \ E_\gamma 545 \pm 5 \text{ MeV}$

<table>
<thead>
<tr>
<th>$\chi^2 / \text{ndf}$</th>
<th>11.6 / 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p0$</td>
<td>-0.004779 ± 0.005589</td>
</tr>
<tr>
<td>$p1$</td>
<td>0.01599 ± 0.003189</td>
</tr>
<tr>
<td>$p2$</td>
<td>-0.005017 ± 0.002166</td>
</tr>
<tr>
<td>$p3$</td>
<td>0.005176 ± 0.001699</td>
</tr>
<tr>
<td>$p4$</td>
<td>-0.002115 ± 0.001286</td>
</tr>
<tr>
<td>$p5$</td>
<td>-6.533e-05 ± 0.001165</td>
</tr>
<tr>
<td>$p6$</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>$p7$</td>
<td>0 ± 0</td>
</tr>
</tbody>
</table>
Σ - Interpretation/Analysis

- $p_2^2$
- $p_3^2$
- $p_4^2$
- $p_5^2$
- $p_6^2$
- $p_7^2$
- Quadrupole Deformation

- $\gamma N \rightarrow \Delta$

M1 ($1^+$) Transition

- E2 ($2^+$) Transition

- E2/M1 Ratio given by

$$\frac{E_2}{M_1} = \frac{1}{2} k M_N \frac{\langle Q_{zz} \rangle_{N\Delta}}{\mu_{n\Delta}}$$  \hspace{1cm} (1)

$$\frac{E_2}{M_1} = 2.5\%$$ \hspace{1cm} (2)

Σ - Quadrupole Deformation

- $\gamma d \rightarrow d^*$

E2 ($2^+$) Transition
M3 ($3^+$) Transition
E4 ($4^+$) Transition
$C_{x'} - Energy\ Variation$
Determination

- In a similar manner can determine $C_{x'}$ by forming the asymmetry

\[
\frac{N^-(\phi_{p'}) - N^+(\phi_{p'})}{N^-(\phi_{p'}) + N^+(\phi_{p'})} = \frac{A_{\text{eff}} P^\odot C_{x'} \sin \phi_{sc}}{1 + A_{\text{eff}} P \cos \phi_{sc}}
\]

- $A_{\text{eff}}$ is the effective analysing power of the charge exchange interaction

- $|A_{\text{eff}}| \sim 0.1 - 0.2$
$C_x'$ - Circular Polarisation

\[ p_\gamma^C(E_\gamma) \]
$C_x^\prime$ - Analysing Power

$A_y (E_n, \theta_{Sc})$

$\theta_{Sc}/\text{Deg}$

$E_r/\text{MeV}$

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$C_{x'}$ - Scattered Frame

- Asymmetry is also determined for the angle $\phi_{sc}$