Charge Symmetry Breaking
in the Reaction $dd \rightarrow {}^4\text{He}\pi^0$ with WASA-at-COSY

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Isospin Symmetry

Two sources of violation:

• Electromagnetic interaction
• Lightest quark mass difference → Window for probing quark-mass effects
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Nucleon mass difference

\[ \Delta M_{np} = \Delta M_{em} + \Delta M_{str} \]

-0.7 ± 0.3 MeV (from QED + dispersion theory)

2.05 ± 0.3 MeV \((\Delta M_{pn} - \Delta M_{em})\)
**Isospin Symmetry**

**Two sources of violation:**
- Electromagnetic interaction
- Lightest quark mass difference $\rightarrow$ Window for probing quark-mass effects

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2.05 ± 0.3 MeV ($\Delta M_{pn} - \Delta M_{em}$)

Link between quark-mass effects and hadronic observables from Chiral Perturbation Theory

$\pi N$ scattering length, e.g., \( a(\pi^0p) - a(\pi^0n) = f(\Delta M_{str}) \) (Weinberg 1977)

However:
- No direct measurement of $\pi^0N$
- Large e.m. corrections in $\pi^\pm N$
Charge Symmetry Breaking

Isospin Symmetry Breaking
Dominated by pion mass difference $\Delta m_\pi$ – e.m. effect

↓

Charge Symmetry (CS) Breaking
Symmetry under the operation of $P^{CSB} - \Delta m_\pi$ does not contribute
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Symmetry under the operation of $P_{CSB}$ - $\Delta m_\pi$ does not contribute

1. $np \rightarrow d\pi^0$ forward-backward asymmetry $A_{fb}$ [1]

$$\Delta M_{str} = (1.5 \pm 0.8 \ (\text{exp.}) \pm 0.5 \ (\text{th.})) \text{ MeV} \ (\text{LO}) \ [2]$$

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1. $np \rightarrow d\pi^0$ forward-backward asymmetry $A_{fb}$ \textsuperscript{[1]}

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2. $dd \rightarrow ^4\text{He}\pi^0$

CS $\Rightarrow \sigma = 0$ \hspace{1cm} CS$\Rightarrow \sigma \neq 0$, $\sigma \propto |M_{CSB}|^2 = |M_1 + M_2 + \ldots |^2$

$\sigma_{\text{total}}$ measured at treshold \textsuperscript{[3]} – result cosistent with s-wave

Chiral Perturbation Theory

Information about higher partial waves in $dd \rightarrow ^4\text{He}\pi^0$ needed
$\rightarrow$ Constraint of the contribution from the $\Delta$ resonance

\textsuperscript{[1]} Opper et al. PRL 91 (2003) 212302 \hspace{1cm} \textsuperscript{[2]} Filin et al. Phys. Lett. B681 (2009) 423
\textsuperscript{[3]} Stephenson et al. PRL 91 (2003) 142302 \hspace{1cm} \textsuperscript{[4]} Adlarson et al. Phys. Lett. B 739 (2014) 44

25.09.2017
M. Żurek - CSB with WASA
WASA-at-COSY experiment

CSB with WASA-at-COSY:

2007: Measurement of $dd \rightarrow ^3He n \pi^0$
goal: description of main background, input for initial-state-interaction calculations

2008: First measurement of $dd \rightarrow ^4He \pi^0$ (2 weeks) @ $Q = 60$ MeV
goal: $\sigma_{\text{total}}$

2014: New measurement of $dd \rightarrow ^4He \pi^0$ (10 weeks) @ $Q = 60$ MeV with modified detector
goal: angular distribution

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Analysis of $dd \rightarrow ^4\text{He}\pi^0$

Background
- $dd \rightarrow (pnd, pnpn, tp) + \pi^0$
- $dd \rightarrow ^3\text{He}\pi^0$ ($3 \cdot 10^5$ higher $\sigma$)
- $dd \rightarrow ^4\text{He}\gamma\gamma$ (physics bg)

Overall kinematic fit
- $2$ hypotheses fitted: $dd \rightarrow ^4\text{He}\gamma\gamma$ and $dd \rightarrow ^3\text{He}\gamma\gamma$

→ Optimized cuts on cumulated probability distribution ($p$-value)
→ Suppression of $dd \rightarrow ^3\text{He}\pi^0$ about $10^4$

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Missing mass of $dd \rightarrow ^4\text{HeX}$

Full angular range within detector acceptance

Luminosity determination using $dd \rightarrow ^3\text{He}n\pi^0$

Four angular bins
Differential cross section

Identical particles in the initial state  
→ forward-backward symmetric cross section

\[ \frac{d\sigma}{d\Omega} = a + b \cos^2 \theta^* \]

fit result:

\[
\begin{align*}
  a &= \left( 1.55 \pm 0.46 \text{(stat)}^{+0.32}_{-0.8} \text{(syst)} \right) \text{ pb/sr} \\
  b &= \left( 13.1 \pm 2.1 \text{(stat)}^{+1.0}_{-2.7} \text{(syst)} \right) \text{ pb/sr}
\end{align*}
\]

Common systematic uncertainty of 10% from external normalization
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Common systematic uncertainty of 10% from external normalization

Considering only *s-* and *p-*waves [1]:
\[
b = -\frac{P_{\pi^0}}{p} \frac{2}{3} |C|^2 p_{\pi^0}^2
\]

- *p-*waves contribute with a **negative** sign → maximum at 90° in angular distribution
- **Observed minimum** at 90° → explained only with *d-*waves in the final state

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**Data establish for the first time presence of sizable contribution of d-waves**

Quantitative results

Including $d$-waves, terms up to fourth order in pion momentum has to be considered:

$$
\frac{d\sigma}{d\Omega} = \frac{p_{\pi 0}^2}{p} \frac{2}{3} \left( |A_0|^2 + 2 \text{Re}(A_0^* A_2) P_2(\cos \theta^*) p_{\pi 0}^2 + |A_2|^2 P_2^2(\cos \theta^*) p_{\pi 0}^4 + |C|^2 \sin^2 \theta^* p_{\pi 0}^2 \right)

+ |B|^2 \sin^2 \theta^* \cos^2 \theta^* p_{\pi 0}^4 \right)$$
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\]

\[
+ \left| B \right|^2 \sin^2 \theta^* \cos^2 \theta^* p_{\pi^0}^4
\]

Assuming that amplitudes do not carry any momentum dependence → simultaneous fit of angular distribution and momentum dependence of total cross section

\[
\sigma_{\text{tot}} = \frac{p_{\pi^0}}{p} \frac{8\pi}{3} \left( |A_0|^2 + \frac{2}{3} |C|^2 p_{\pi^0}^2 + \frac{1}{5} |A_2|^2 p_{\pi^0}^4 + \frac{2}{15} |B|^2 p_{\pi^0}^4 \right)
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\]

Systematic check of the fit:

- \( |B|^2 \) – consistent with 0 within the fit error
- \( |C|^2 \) – consistent with 0 within the fit error
- Other parameters: stable within the fit error
→ Assumption about \( |A_0|^2 \) momentum independence reasonable
→ Relative phase \( \delta \) between \( A_0 \) and \( A_2 \): 0 with a statistical uncertainty in the range ±(1.0 – 1.6) rad
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\]

Final result of the simultaneous fit:

$B$ – fixed to 0, phase $\delta$ – fixed to 0

$|A_0| = (5.77 \pm 0.35(\text{stat})^{+0.08}_{-0.33}(\text{syst})^{+0.01}_{-0.19}(\text{norm})) \ (\text{pb}/\text{sr})^{1/2}$

$|A_2| = (255 \pm 59(\text{stat})^{+48}_{-38}(\text{syst})^{+37}_{-12}(\text{norm})) \ (\text{pb}/\text{sr})^{1/2} / (\text{GeV}/c)^2$

$|C| = (4 \pm 38(\text{stat})^{+9}_{-10}(\text{syst})^{+10}_{-6}(\text{norm})) \ (\text{pb}/\text{sr})^{1/2} / \text{GeV}/c$

Obtained total cross section:

\[
\sigma_{\text{tot}} = (76.9 \pm 7.8(\text{stat})^{+1.9}_{-8.8}(\text{syst})^{+8.3}_{-5.7}(\text{norm})) \ \text{pb}.
\]
Conclusions

- **First measurement of contributions of higher partial waves** in the charge symmetry breaking reaction \( dd \rightarrow ^4\text{He}\pi^0 \)
- Angular distribution with a minimum at \( \theta^* = 90^\circ \) can be understood only by the presence of a **significant d-wave contribution** in the final state
- Data are consistent with **vanishing p-wave** contribution
  
  Role of the \( \Delta \) isobar ?
  
- Deep insights not only into the dynamics of the nucleon-nucleon interaction but also the role of **quark masses in hadron dynamic**
Backup
Leading diagrams of CSB reactions

Formally leading operators for $p$-wave pion production in $dd \rightarrow ^4\text{He}\pi^0$.

Leading order diagram for the CSB $s$-wave amplitudes of the $np \rightarrow d\pi^0$ reaction