Eta Meson Production in Proton-Deuteron Collisions

MESON 2014: 13th International Workshop on Meson Production, Properties and Interaction
29th May - 3rd June 2014

Institut für Kernphysik

Alfons Khoukaz
Why $\eta$-Meson Production Close to Threshold?

- Attractive $S$-wave $\eta N$ interaction
  

- Possible formation of $\eta$-nucleus bound states
  

- Broad $\eta$-mesic nuclei program at COSY
  
  - $A>4$: GEM ($\eta^7\text{Be}$)
  - $\eta^4\text{He}$: ANKE, GEM, WASA-at-COSY
  - $\eta^3\text{He}$: ANKE, COSY11, GEM, WASA-at-COSY
  - $\eta d$: ANKE

- New data from proton-deuteron collisions
Why $\eta$-Meson Production Close to Threshold?

• Do bound meson-nucleus systems exist?

• Experimental access e.g. via $d+p \rightarrow ^3\text{He}+\eta$
  $\gamma+^3\text{He} \rightarrow ^3\text{He}+\eta$

• Excitation function close to threshold $\rightarrow$ FSI

• Polarized beam $\rightarrow$ Test of FSI hypothesis, role of spins
Results for the Reaction $d+p \rightarrow ^3\text{He}+\eta$

- A good candidate for a bound state is the $\eta^3\text{He}$-system
  - High precision data from ANKE and COSY-11
  - Observation of strong FSI
  - Strong indication for a pole at $|Q_0| \approx 0.37$ MeV
  - Further evidence for pole hypothesis by angular dependence of $dp \rightarrow \eta^3\text{He}$

Data: ANKE Collaboration

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{p_f}{p_i} \cdot \frac{|f_{\text{prod}}|^2}{1 - i \cdot a \cdot p_f + \frac{1}{2} a \cdot r_0 \cdot p_f^2}$$

The $d+p \rightarrow ^3\text{He}+\eta$ Scattering Amplitude

Extracted scattering amplitude ($Q > 0$ MeV)

- Scattering amplitude decreases rapidly with increasing final state momentum $p_f$
- Scattering amplitude almost constant at high energies

$\frac{d\sigma(\theta)}{d\Omega} \propto \frac{p_f}{p_i} \left| \frac{f_{\text{prod}}}{1 - \frac{p_f}{p_1}} \cdot \frac{1 - \frac{p_f}{p_2}}{1 - \frac{p_f}{p_1}} \right|^2$

$\rightarrow$ strong FSI in $\eta^3\text{He}$ system
Consideration of Higher Partial Waves: *P*-Waves

- Close to threshold: \( \frac{d\sigma}{d\Omega}(\theta) = \text{const.} \) \( \rightarrow s\text{-wave} \)
- \( Q > \sim 4 \text{ MeV} \): Contributions \( \sim \cos(\theta) \) visible \( \rightarrow p\text{-wave} \)

- Asymmetry in the angular distribution (\( \eta \)-meson):
  Slope at \( \cos(\theta)=0 \):
  \[
  \alpha = \frac{d}{d(\cos \theta_\eta)} \ln \left( \frac{d\sigma}{d\Omega} \right)_{\cos \theta_\eta=0}
  \]
  \[
  \left( \frac{d\sigma}{d\Omega} \right)_{CM} = \frac{\sigma_{tot}}{4\pi} \cdot \left( 1 + \alpha \cdot \cos \theta_{CM} \right)
  \]
Consideration of Higher Partial Waves: \textit{P}-Waves

- Slope might arises from the interference between the \textit{s}- and \textit{p}-waves in the \(\eta^3\)He system
- Indication of a \textbf{strong phase variation} of the \textit{s}-wave at low \(Q\)
- Data (\(\sigma_{\text{total}}\) and \(d\sigma/d\Omega\)) can be described well by assumption of a \textbf{pole close to threshold}

\[
\left(\frac{d\sigma}{d\Omega}\right)_{\text{CM}} = \frac{\sigma_{\text{tot}}}{4\pi} \cdot (1 + \alpha \cdot \cos \theta_{\text{CM}})
\]

Consideration of Higher Partial Waves: $P$-Waves

- Assumption: Only $s$- and $p$-waves

Production operator:

\[ \hat{f} = A \vec{e} \cdot \hat{p}_p + iB(\vec{e} \times \vec{\sigma}) \cdot \hat{p}_p + C \vec{e} \cdot \hat{p}_\eta + iD(\vec{e} \times \vec{\sigma}) \cdot \hat{p}_\eta \]

- $A, B$: $s$-wave amplitudes
- $C, D$: $p$-wave amplitudes
- $\vec{\varepsilon}$: polarisation vector of the deuteron

\[ \frac{d\sigma}{d\Omega} = \frac{p_\eta}{p_p} |\hat{f}|^2 = \frac{p_\eta}{3p_p} I \]

\[ I = |A|^2 + 2|B|^2 + p_\eta^2 |C|^2 + 2p_\eta^2 |D|^2 + 2p_\eta Re(A \ast C + 2B \ast D) \cos \theta_\eta \]

C. Wilkin et al., PLB 654 (2007) 92
Consideration of Higher Partial Waves: $P$-Waves

• Resulting asymmetry factor:

$$\alpha = 2p_\eta \frac{\text{Re}(A*C + 2B*D)}{|A|^2 + 2|B|^2 + p_\eta^2|C|^2 + 2p_\eta^2|D|^2}$$

Assumption:

• Same $s$-wave amplitudes:

$$A = B = f_s$$

energy dependence due to FSI

• Same $p$-wave amplitudes:

$$C = D = \text{const.}$$

$$\sigma = 4\pi \frac{p_\eta}{p_p} \left[ |f_s|^2 + p_\eta^2|C|^2 \right]$$

$$\alpha = 2p_\eta \frac{\text{Re}(f_s*C)}{|f_s|^2 + p_\eta^2|C|^2}$$
Compare: dp- and $\gamma^3\text{He}$-Scattering

- Different initial states and production mechanism, but same final state
Compare: dp- and $\gamma^3$He-Scattering

- Scattering amplitudes show similar energy dependence
- Strong hint for a strong FSI between He-nuclei and $\eta$-mesons

F. Pheron et al., PLB 709 (2012) 21-27
Compare: \( dp \)- and \( \gamma^3\text{He} \)-Scattering

- Scattering amplitudes show similar energy dependence
- Strong hint for a strong FSI between He-nuclei and \( \eta \)-mesons
Compare: dp- and $\gamma^3\text{He}$-Scattering

\[ d+p \rightarrow ^3\text{He}+\eta \]

\[ \eta \text{ momentum } p_\eta \text{ [MeV/c]} \]

C. Wilkin et al., PLB 654 (2007) 92

\[ \alpha = \frac{d}{d(\cos\theta_\eta)} \ln \left( \frac{d\sigma}{d\Omega} \right)_{\cos\theta_\eta=0} \]

\[ \frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{tot}}}{4\pi} \cdot (1 + \alpha \cdot \cos\theta_{\text{CM}}) \]
Need of Further Data

- Excitation function(s) and differential cross sections for the \( \eta - ^{3}\text{He} \) final state are compatible with the presence of a pole close to threshold.
- Further input is needed to investigate e.g. the role of the spin of the entrance channel.
- Very close to threshold the \( \text{d} + \text{p} \rightarrow ^{3}\text{He} + \eta \) reaction is dominated by an \textit{s-wave} \(^{3}\text{He} + \eta \) system.
- ANKE: Studies with tensor polarised deuterons \( \overrightarrow{\text{d}} \overrightarrow{\text{p}} \rightarrow ^{3}\text{He} + \eta \)
  Possible spins: \( S_{\text{dp}} = 1/2 \) or \( 3/2 \)
Polarized Measurements

Production amplitude for $dp \rightarrow ^3\text{He} + \eta\left(\pi^0\right)$:

$$f_B = \bar{u}_\tau \vec{p}_p \cdot (A \vec{e}_d + iB \vec{e}_d \times \vec{\sigma})u_p$$

Determinination of the energy dependence of the amplitudes $A$ and $B$ by measurement of:

$$\frac{d\sigma}{d\Omega} = \frac{1}{3} \frac{p_\eta}{p_p} \left[ |A|^2 + 2|B|^2 \right]$$

$$|A|^2 = \frac{p_p}{p_\eta} (1 - \sqrt{2}T_{20}) \frac{d\sigma}{d\Omega}$$

$$T_{20} = \frac{2}{p_{zz}} \frac{d\sigma_0}{d\Omega(\vartheta)} - \frac{d\sigma_1}{d\Omega(\vartheta)}$$

$$|B|^2 = \frac{p_p}{p_\eta} (1 + \frac{1}{\sqrt{2}T_{20}}) \frac{d\sigma}{d\Omega}$$

$$T_{20} = \sqrt{2} \frac{|B|^2 - |A|^2}{|A|^2 + 2|B|^2}$$

$$\vartheta = 0^0 \text{ or } 180^0$$
Polarized Measurements

Assumption for $\vec{dp} \rightarrow ^3\text{He} + \eta$:

- Negligible effect of ISI
- Energy dependence of $|f|^2$ only given by FSI
  → Shape of excitation function independent of spins
  → Same energy dependence of amplitudes $|A|^2$ and $|B|^2$

\[
|A|^2 = |A_0|^2 \cdot \text{FSI}(p_\eta) \\
|B|^2 = |B_0|^2 \cdot \text{FSI}(p_\eta)
\]

\[
\Rightarrow \quad T_{20} = \sqrt{2} \left[ \frac{|B_0|^2 - |A_0|^2}{|A_0|^2 + 2|B_0|^2} \right] \frac{\text{FSI}(p_\eta)}{\text{FSI}(p_\eta)} = \text{const.}
\]

- Measure $T_{20}$ as function of the excess energy
Recent results from ANKE: $d+p \rightarrow ^3\text{He}+\eta$

- Data close to threshold consistent with $T_{20} = \text{const.}$

  $T_{20} = -0.21 \pm 0.02 \pm 0.05$

- $|T_{20}| \ll 1 \rightarrow |A|^2/|B|^2 = O(1)$

- $S$-Wave amplitudes $|A|^2$ and $|B|^2$ are of similar size
Recent Results: $d+p \rightarrow ^3\text{He}+\eta$

- Energy dependence of $|f|^2$ known from "old" unpolarized measurements
  
  $|A|^2(p_f)$ and $|B|^2(p_f)$ can be calculated

\[
|f|^2 = |A|^2 + 2|B|^2
\]

\[
\frac{d\sigma}{d\Omega} = \frac{1}{3} \frac{p_\eta}{p_p} \left[ |A|^2 + 2|B|^2 \right]
\]

\[
|A|^2 = \frac{p_p}{p_\eta} \left( 1 - \sqrt{2T_{20}} \right) \frac{d\sigma}{d\Omega}
\]

\[
|B|^2 = \frac{p_p}{p_\eta} \left( 1 + \frac{1}{\sqrt{2}} T_{20} \right) \frac{d\sigma}{d\Omega}
\]

M. Papenbrock, nucl-ex/1404.5425, accepted by PLB
Recent Results: $d+p \rightarrow ^3\text{He}+\eta$

- Allow for a linear energy dependence of $T_{20}$ and $|A|^2/|B|^2$:

$$T_{20} = (-0.14 \pm 0.04) + (-0.02 \pm 0.01)Q$$

$$\frac{|B|^2}{|A|^2} = (0.75 \pm 0.06) - (0.014 \pm 0.014)Q$$

→ Possible energy variation of $|A|^2(p_f)$ and $|B|^2(p_f)$ on the scale of $0.75/0.014 \text{ MeV} \approx 50 \text{ MeV}$
Recent Results: $d+p \rightarrow ^3\text{He}+\eta$

- No significant different energy dependence of $|A|^2$ and $|B|^2$
- Remarkable excitation function of $d+p \rightarrow ^3\text{He}+\eta$ still an indication for very strong FSI effect

M. Papenbrock, nucl-ex/1404.5425, accepted by PLB
Angular Dependence of $T_{20}$

- Asymmetry parameter: $\alpha = \frac{dT_{20}}{d \cos \theta} \bigg|_{\cos \theta = 0}$
  - sensitive to interferences between even and odd $\eta$ partial waves
  - odd function of $p_\eta$ with $\alpha(Q=0) = 0$

- No sign for any $s$-$p$ interference here

But:
- Unpolarized data show already at $Q = 4$ MeV a non-isotropy $d\sigma/d\Omega$

---

M. Papenbrock, nucl-ex/1404.5425, accepted by PLB
Ansatz for Structure of Amplitudes $A$ and $B$

\[
A = A_0 \left[ FSI(p_\eta) + \alpha p_\eta \cos \vartheta + \beta p_\eta^2 (3\cos^2 \vartheta - 1)/2 \right] \\
B = B_0 \left[ FSI(p_\eta) + \alpha p_\eta \cos \vartheta + \beta p_\eta^2 (3\cos^2 \vartheta - 1)/2 \right]
\]

- FSI term influences only the $s$-wave term
- $A$ proportional to $B \rightarrow T_{20}$ independent of $p_\eta$ and $\vartheta$
- Ansatz allows for observed non-isotropy of $d\sigma/d\Omega$ at higher excess energies
Ansatz for Structure of Amplitudes A and B

\[
A = A_0 \left[ FSI(p_\eta) + \alpha p_\eta \cos \vartheta + \beta p_\eta^2 (3\cos^2\vartheta - 1)/2 \right]
\]

\[
B = B_0 \left[ FSI(p_\eta) + \alpha p_\eta \cos \vartheta + \beta p_\eta^2 (3\cos^2\vartheta - 1)/2 \right]
\]

- Unpolarized data show linearity in \(d\sigma/d\Omega\) for \(Q > 4\) MeV
- Can be explained by cancellation of interference between \(s\) and \(d\) waves and the square of \(p\) waves

→ Important new information on \(|f|^2\)

T. Mersmann et al., PRL 98 (2007) 242301
The Reaction $d+p \rightarrow ^3\text{He}+\eta$ at Higher Q-Values

• Good understanding of the production mechanism is important for an even better investigation of the FSI effects at threshold and/or of possible bound states
• Threshold data are not sufficient for solid investigations
  • FSI effects dominate very close to threshold
    → data at higher excess energies (>10 MeV) important
• New differential cross section data from WASA-at-COSY recently published ($Q = 48.8$ MeV & 59.8 MeV)
Recent Results from WASA-at-COSY

- Angular distributions show strong anisotropy
- Precise determination of total cross section ratio

But
- Theoretical models (e.g. two-step process) completely fail to explain total & differential cross sections

\[
\frac{\sigma(48.8\text{MeV})}{\sigma(59.8\text{MeV})} = 0.77 \pm 0.06
\]
Development of Angular Distributions

ANKE

WASA-at-COSY

WASA-Promice

WASA-Promice

WASA-at-COSY
Predictions from a Two-Step Model

Fig. 1. Diagram of $\eta$ production in the $pd \rightarrow ^3He \eta$ reaction with a two step process. The ellipse indicates the final state interaction of $^3He$ and $\eta$.


The Reaction $d+p \rightarrow ^3\text{He}+\eta$ at Higher Q-Values

- Recent data might indicate a cross section variation at higher excess energies, i.e. at 20 MeV...60 MeV

New WASA-at-COSY data (red) arbitrarily scaled to the 60 MeV ANKE point

$\frac{\sigma_\eta(48.8 \text{ MeV})}{\sigma_\eta(59.8 \text{ MeV})} = 0.77 \pm 0.06$

Normalization uncertainties not included

P. Adlarson et al., accepted by EPJA
The Reaction $d+p \rightarrow ^3\text{He}+\eta$ at Higher Q-Values

- Recent data might indicate a cross section variation at higher excess energies, i.e. at 20 MeV...60 MeV

New WASA-at-COSY data (red) arbitrarily scaled to the 60 MeV ANKE point

Normalization uncertainties not included

Cross section structure?

P. Adlarson et al., accepted by EPJA
The Reaction \( \text{d} + \text{p} \rightarrow ^3\text{He} + \eta \) at Higher Q-Values

- Current data base for \( Q > 20 \text{ MeV} \) not sufficient for solid investigations → new data needed
- Very recently new high statistics data have been recorded at WASA-at-COSY at 15 Q-values, i.e. in the interval \( Q = 14 \text{ MeV} - 88 \text{ MeV} \)
- Precise total and differential cross sections can be expected for the future (>100 kevents per energy!)
- Solid data base for further investigations on
  - Production processes
  - Possible cross section structures
WASA-at-COSY Beam Time: May 2014

„Online spectra“ from supercycle 2: 8 energies

\[ Q = 18 \text{ MeV} \quad Q = 28 \text{ MeV} \quad Q = 38 \text{ MeV} \quad Q = 48 \text{ MeV} \]

\[ Q = 57 \text{ MeV} \quad Q = 62 \text{ MeV} \quad Q = 67 \text{ MeV} \quad Q = 77 \text{ MeV} \]

Nils Hüsken, private communication
The Reaction $d+p \rightarrow {}^{3}\text{He}+\eta$ at Higher Q-Values

Normalization uncertainties not included

New WASA-at-COSY data

P. Adlarson et al., accepted by EPJA
Outlook: \( pd \rightarrow p_{sp} d \eta \)

- Threshold enhancement \( \sigma/PS \leftrightarrow FSI \) calculations
- Filled symbols: \( pd \rightarrow pd \eta \) taken below \( NN \rightarrow NN \eta \) threshold

\[ \eta N \text{ input} \quad \eta N \text{ input} \]
<table>
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<th>Ref.</th>
<th>( a_{\eta N} ) (fm)</th>
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<th>MST II [8]</th>
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<td>0.25+0.16</td>
<td>0.73+0.56</td>
<td>0.66+0.71</td>
<td>0.66+0.58</td>
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\[ \left| f(p_f) \right|^2 = \frac{S}{1 - i \cdot a_{\eta N} \cdot p_f} \]
Outlook: \(pd \rightarrow p_{sp}d\eta\)

- New data from ANKE/COSY are expected to allow for
  - a scattering length \(|a_{d\eta}|\) determination with a precision of \(~5\%\)
  - the determination of angular distributions

in the excess energy range \(Q = 0...100\) MeV

- First signals: Subtraction from two data sets obtained at different beam momenta, but analyzed assuming the same beam momentum

Daniel Schröer, private communication
Summary

- New data on \( \eta \) meson production in pd-collisions give important information on \( \eta \)-nucleus systems
- Results from measurements with polarized beams
  - support the strong \( ^3\text{He}+\eta \) FSI interpretation
  - show no spin-dependent contributions on a scale of \(~\text{MeV}\) above threshold
  - give new insight into the structure of the relevant production amplitudes
- Data at higher excess energies might indicate an unexpected cross section structure
- New data have been recorded recently and will allow for more detailed experimental and theoretical investigations
Thank you very much....
We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters B204 (1988).

**η MASS**

Recent measurements resolve the obvious inconsistency in previous η mass measurements in favor of the higher value first reported by NA48 (LAI 02). We use only precise measurements consistent with this higher mass value for our η mass average.

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* We do not use the following data for averages, fits, limits, etc. • • •

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1 ABDEL-BARY 05 disagrees significantly with recent measurements of similar or better precision. See comment in the header.
The COSY-Accelerator at Jülich

Energy range
- 0.045 – 2.8 GeV (p)
- 0.023 – 2.3 GeV (d)
  (momentum 3.7 GeV/c)

Beam cooling
- Electron cooling
- Stochastic cooling

Polarisation
- p, d beams & targets

Beams
- internal, external

Experiments, Detectors
- ANKE, TOF, WASA, …
The Experiments ANKE and WASA-at-COSY
Scattering Theory and Final State Interaction

• The scattering length can deliver informationen about possible bound states

• Conditions for bound $\eta^3\text{He}$ state:
  - Existence of a pole in the complex $p_f$ plane

\[
 f_s = \frac{f_{\text{prod}}}{1 - i \cdot a \cdot p_f + \frac{1}{2} a \cdot r \cdot p_f^2}
\]

\[
 a \equiv a_r + i a_i
\]

\[
 r \equiv r_r + i r_i
\]

• As well as

\[
 a_r < 0, \quad a_i > 0, \quad R = \frac{|a_i|}{|a_r|} < 1
\]
η–³He Scattering Length

Fit to data delivers information about the complex η–³He scattering length:

\[
\left( \frac{d\sigma(\mathcal{I})}{d\Omega} \right) \cdot \frac{p_i}{p_f} = |f_{\text{scat}}|^2 = |f_{\text{prod}} \cdot FSI|^2 = |f_{\text{prod}}|^2 \cdot |FSI|^2
\]

Result:

\[
a = \left[ \pm \left( 10.7 \pm 0.8_{-0.5}^{+0.1} \right) + i \left( 1.5 \pm 2.6_{-0.9}^{+1.0} \right) \right] \text{fm}
\]

Notice: Determination of |a_r|!

$\eta^-{^3}\text{He}$-Interaction: Determination of Pols

\[
\left( \frac{d\sigma(\mathcal{E})}{d\Omega} \right) \cdot \frac{p_i}{p_f} = |f_{\text{scatt}}|^2 = |f_{\text{prod} \cdot FSI}|^2 = |f_{\text{prod}}|^2 \cdot |FSI|^2
\]

FSI = \frac{1}{1 - i \cdot a \cdot p_f + \frac{1}{2} a \cdot r_0 \cdot p_f^2}

FSI = \frac{1}{\left(1 - \frac{p_f}{p_1}\right) \cdot \left(1 - \frac{p_f}{p_2}\right)}

\begin{align*}
a &= -i \cdot \frac{p_1 + p_2}{p_1 \cdot p_2} \\
r_0 &= + \frac{2 \cdot i}{p_1 + p_2}
\end{align*}

\begin{align*}
p_1 &= \left[(-5 \pm 7_{-1}^{+2}) \pm i \cdot (19 \pm 2 \pm 1)\right] \text{MeV/c} \\
p_2 &= \left[(106 \pm 5) \pm i \cdot (76 \pm 13_{-2}^{+1})\right] \text{MeV/c}
\end{align*}
The Reaction $d+p \rightarrow ^3\text{He}+\eta$ at ANKE

- Alternating injection of unpolarized and tensor polarized deuterons in COSY
- Ramped COSY beam: $Q = -5$ MeV ... +10 MeV (300 s)
- Full geometrical acceptance of ANKE for $d+p \rightarrow ^3\text{He}+\eta$
- Determination of $p_{zz}$ by, e.g., $d+p \rightarrow (pp)+n$ (analyzing powers known)

$$\frac{d\sigma^\uparrow}{dt}(q,\phi)/\frac{d\sigma_0}{dt}(q,\phi) = 1 + \sqrt{3} p_z t_{11}(\vartheta) \cos(\phi) - \frac{1}{2\sqrt{2}} p_{zz} t_{20}(\vartheta)$$

$$- \frac{\sqrt{3}}{2} p_{zz} t_{22}(\vartheta) \cos(2\phi)$$
Tensor Polarizations

- Three different polarizations used for the experiment

1.) Nominal: \( p_{zz} = -1, \quad p_z = +1/3 \)
   Measured: \( p_{zz} = -0.635 \pm 0.087 \)

2.) Nominal: \( p_{zz} = +1, \quad p_z = -1 \)
   Measured: \( p_{zz} = 0.529 \pm 0.077 \)

3.) Nominal: \( p_{zz} = +1, \quad p_z = +1 \)
   Measured: \( p_{zz} = 0.217 \pm 0.082 \)