Investigation on the tensor analyzing power $t_{20}$ in the reaction $\vec{d} + p \rightarrow ^3\text{He} + \eta$

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Motivation

- Previous unpolarized measurements on $dp \rightarrow ^3\text{He}\eta$ provided detailed cross section data near the production threshold.
- Excitation function has shown indications of an unexpected strong final state interaction (FSI).

Test for contributions to the cross section other than FSI possible by polarized measurements.

ANKE: Investigation of the reaction with a tensor/vector polarized deuteron beam.
Measuring $dp \rightarrow ^3\text{He}\eta$ at ANKE at COSY

- Internal fixed target experiment with a cluster-jet target
- $^3\text{He}$ nuclei detected in the forward-system
- Full geometrical acceptance for $dp \rightarrow ^3\text{He}\eta$ up to 20 MeV excess energy
Acceptance of the ANKE detector system

- Full acceptance for $dp \rightarrow ^3\text{He}\eta$
- Continuously ramped beam from $Q = -5 \text{ MeV}$ to $Q = 11 \text{ MeV}$
High precision $\eta$ mass determination

![Graph showing the relationship between beam momentum $p_d$ [GeV/c] and final state momentum $p_f$ [GeV/c]].
ANKE-COSY result of the $\eta$ mass

\[ m_\eta = (547.873 \pm 0.005_{\text{stat.}} \pm 0.023_{\text{sys.}}) \text{ MeV/c}^2 \]

ANKE $\eta$ meson mass

- Highest precision measurement yet
- In agreement with higher $\eta$ meson mass measurements
- Published in Physical Review D85, 112011 (2012)
\(^3\text{He}\eta\) final state interaction

Description of the differential cross section

- Differential cross section of a two-body reaction:
  \[
  \frac{p_i}{p_f} \cdot \frac{d\sigma}{d\Omega} = |f|^2 = |f_B \cdot FSI|^2 = |f_B|^2 \cdot |FSI|^2
  \]

- Effective range approximation:
  \[FSI = \frac{1}{1 + i \cdot a \cdot p_f + \frac{1}{2} a \cdot r_0 \cdot p_f^2}\]

- Alternative description with poles:
  \[FSI = \frac{1}{\left(1 - \frac{p_f}{p_1}\right) \cdot \left(1 - \frac{p_f}{p_2}\right)}\]

  with \(a = -i \cdot \frac{p_1 + p_2}{p_1 \cdot p_2}\) and \(r_0 = +\frac{2 \cdot i}{p_1 + p_2}\)
$^3\text{He}\eta$ final state interaction: unpolarized data

- Very good description for the whole energy range
- Pole close to threshold ($|Q_0| \approx 0.4$ MeV) might be an indication for a quasi-bound state
Investigation of the reaction $pn \rightarrow d\eta$

- Investigation of A dependence of the $\eta$-nucleus FSI
- further important information about $\eta$-mesic nuclei
- Determination of $d\eta$ scattering length
- information about still unprecisely known $\eta N$ scattering length

- Measurement has been performed earlier this year
Why polarised measurements?

Additional information for FSI ansatz needed

- Test for further contributions besides FSI
- Investigate production amplitude close to threshold

Alternative description of the $\eta^3\text{He}$ s-wave production amplitude:

$$f = \bar{u}_{3\text{He}} \hat{p}_p \cdot (A\vec{\varepsilon}_d + iB\vec{\varepsilon}_d \times \vec{\sigma}) u_p$$


$$\frac{d\sigma}{d\Omega} = \frac{1}{3} \frac{p_f}{p_i} \left[ |A|^2 + 2 \cdot |B|^2 \right]$$

with $A$, $B$ as the two s-wave amplitudes of the $^3\text{He}\eta$ system
Why polarised measurements?

**Assumption 1** Cross sections only differ from phase space because of FSI  
⇒ $A, B$ show same energy dependence

**Assumption 2** Cross sections depend on spin dependent production amplitudes (no FSI effect)  
⇒ $A, B$ might show different energy dependence

How to separate $|A|^2$ and $|B|^2$?  
⇒ Tensor analysing power $t_{20}$:  

$$t_{20}(p_f) = \sqrt{2} \frac{|B|^2 - |A|^2}{|A|^2 + 2|B|^2}$$
Why polarised measurements?

Assumption: $|A|^2$ and $|B|^2$ only depend on FSI

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

\[ \Rightarrow t_{20}(p_f) = \sqrt{2} \cdot \frac{|B_0|^2 - |A_0|^2}{|A_0|^2 + 2|B_0|^2} \cdot \frac{\text{FSI}(p_f)}{\text{FSI}(p_f)} = \text{const.} \]

Measure $t_{20}$ in collinear kinematics

\[ t_{20}(p_f) = \frac{2\sqrt{2}}{p_{zz}} \cdot \left( \frac{d\sigma^0}{d\Omega}(\vartheta) - \frac{d\sigma^\uparrow}{d\Omega}(\vartheta) \right) \]
Determining $p_{zz}$

Investigate reaction $d + p \rightarrow (pp) + n$ with known analyzing powers at lower energy ($T_d = 1.2 \text{ GeV}$)

\[
\frac{d\sigma^\uparrow}{dt}(q, \varphi)/\frac{d\sigma^0}{dt}(q) = 1 + \sqrt{3}p_{zt1}(\vartheta) \cos \varphi \\
- \frac{1}{2\sqrt{2}}p_{zz}t_{20}(\vartheta) - \frac{\sqrt{3}}{2}p_{zz}t_{22}(\vartheta) \cos 2\varphi
\]
Determining $t_{20}$

- Reminder:

$$t_{20}(p_f) = \frac{2\sqrt{2}}{p_{zz}} \cdot \left( \frac{d\sigma^0}{d\Omega}(\vartheta) - \frac{d\sigma^\uparrow}{d\Omega}(\vartheta) \right) \quad \vartheta = 0^\circ, 180^\circ$$

- Hence:

$$t_{20}(p_f) = \frac{2\sqrt{2}}{p_{zz}} \left( 1 - \frac{N^\uparrow}{N^0} \right)$$

$N^\uparrow, N^0$ are normalized counts
Data on $t_{20}$ consistent with Berger, et al.

No energy dependence visible within uncertainties
Current status

- Allow slope to put upper limit on spin dependent contributions
Summary

- Studied reaction $\bar{d} + p \rightarrow ^3\text{He} + \eta$ in energy range $Q = -5 \text{ MeV} \text{ to } 15 \text{ MeV}$ relative to $\eta$-threshold.
- No energy dependence of $t_{20}$ observed, $t_{20}$ consistent with Berger, et al.
- Amplitudes $A$, $B$ show same energy dependence within uncertainties.
- Ratio of $|A|^2/|B|^2$ will allow to quantify spin dependent contributions.
- Threshold behavior of $d + p \rightarrow ^3\text{He} + \eta$ consistent with pure FSI ansatz.

Final data available soon.
Thank you for your attention
Additional Slides
Production amplitude

- Two independent $\eta$ s-wave amplitudes (close to threshold)
- Possible dp spin combinations: $S = \frac{3}{2}, \frac{1}{2}$
- Couples with orbital angular momentum of dp: $L_{dp} = 1$
  $\Rightarrow J = \frac{1}{2}$
- Alternative production amplitude used for analogous $\pi^0$ production

$$f = \bar{u}_{3\text{He}} \hat{p}_p \cdot (A\vec{\varepsilon}_d + iB\vec{\varepsilon}_d \times \vec{\sigma}) u_p$$

- $\bar{u}_{3\text{He}}$: Spinors of the particles
- $\vec{\varepsilon}_d$: Polarisation vector of the deuteron
- $\hat{p}_p$: Direction of momentum
- $\vec{\sigma}$: Pauli matrix
$^3\text{He}\eta$ final state interaction

- Fit to the data for $Q < 11\text{MeV}$

$$p_1 = \left[\left(-5 \pm 7^{+2}_{-1}\right) \pm i \cdot (19 \pm 2 \pm 1)\right] \frac{\text{MeV}}{c}$$

$$p_2 = \left[(106 \pm 5) \pm i \cdot (76 \pm 13^{+1}_{-2})\right] \frac{\text{MeV}}{c}$$

- Pole of the production amplitude:

$$Q_0 = \left(\frac{p_1^2}{2 \cdot m_{\text{red}}}\right)$$

$$= \left[\left(-0.30 \pm 0.15 \pm 0.04\right) \pm i \cdot (0.21 \pm 0.29 \pm 0.06)\right] \text{MeV}$$

$$|Q_0| \approx 0.4$$

- Pole close to threshold expected from a quasi-bound state
$^3\text{He}\eta$ final state interaction

- Very good description for the whole energy range
- Unexpected large scattering length:

$$a_{^3\text{He}\eta} = \left[ \pm \left( 10.7 \pm 0.8^{+0.1}_{-0.5} \right) + i \cdot \left( 1.5 \pm 2.6^{+0.3}_{-1.0} \right) \right] \text{ fm}$$