Study of coherent pion production in proton-deuteron collisions with polarized beams and target at ANKE-COSY

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Study of $pd \rightarrow ^3\text{He}\pi^0$ at ANKE (1)

Simplest coherent $\pi$ production process: $pp \rightarrow d\pi^+$

- Extensive database and accurate PSA
- But: symmetric initial state, no $S$ and $P$ interference in cross section

First more general process: $pd \rightarrow ^3\text{He}\pi^0$/$^3\text{H}\pi^+$

- $S$-$P$ interference observed already at $T_{\pi}^{cm} \sim 1$ MeV
- One isospin amplitude $\sigma(3\text{H}\pi^+) = 2 * \sigma(3\text{He} \pi^0)$, equal polarization observables
- But the spin structure is $\frac{1}{2}^+ 1^+ \rightarrow \frac{1}{2}^+ 0^-$
  - six independent spin amplitudes, many observables required
Study of $pd \to ^3\text{He} \pi^0$ at ANKE (2)

Only two spin amplitudes are left at 0, 180°:

$$F(dp \to ^3\text{He} \pi^0) = \overline{u}_\tau \ p \cdot (A\epsilon + iB\epsilon \times \sigma)u_p.$$  

Here $\epsilon$ is the deuteron polarisation vector, $p$ and $k$ the proton and pion c.m. momenta, and $u_p$ and $u_\tau$ are the initial and final fermion spinors.

Amplitudes $A$, $B$ can be extracted from
- Cross section
- Tensor analyzing power
- Transverse spin correlation

\[
\frac{d\sigma}{d\Omega} = \frac{kp}{3} (|A|^2 + 2|B|^2),
\]

\[
T_{20} = \sqrt{2} \frac{|B|^2 - |A|^2}{|A|^2 + 2|B|^2},
\]

\[
C_{y,y} = -\frac{2Re(A^*B)}{|A|^2 + 2|B|^2}.
\]

**Saclay** data  

Provide cross section and $T_{20}$ at 0 and 180° at $T_d=0.5 – 2.2$ GeV

- Moduli of $A$ and $B$
- ANKE can measure spin correlations $C_{y,y}$ and $C_{x,x}$
- Relative phase
Experiment: ANKE@COSY

Cooler Synchrotron COSY at Juelich provides \textit{polarized proton} and \textit{deuteron} beams of 600 – 3700 MeV/c momentum.

The ANKE spectrometer at internal target position of COSY allows measurement of:

- Fast forward positive and negative ejectiles in \textit{Forward, Positive} and Negative detectors (FD, PD, ND): momentum, \textit{Id} by TOF, \textit{dE/dX}

- Slow p/d in Silicon tracking telescope \textit{(STT)}: energy, tracking, \textit{Id} by \textit{dE/dX}

Targets available:
- Cluster jet $\text{H}_2$ and $\text{D}_2$
- Internal polarized ($\text{H}$, $\text{D}$) target (PIT) with a storage cell
Measurement of $A_y^p$ in $\vec{p}d \rightarrow ^3\text{He }\pi^0$ @ 353 MeV

Byproduct of a study of $\vec{p}d \rightarrow \{pp\}_s \pi^0 + p_{\text{spec}}$ (PLB 712 (2012) 375)

- Vert. polarized proton beam: $P_y = 65\%$
  - spin flipped every 5 min
- $D_2$ cluster jet target: $d = 5 \cdot 10^{14} \text{ cm}^{-2}$
- $^3\text{He}, ^3\text{H}$ detected in Fd

Polarimetry, normalization:
with quasi-free $pn \rightarrow d\pi^0$ via $pd \rightarrow d\pi^0 + p_{\text{spec}}$

- Cross section, $A_y$ from SAID database
- spectator proton in STT
- deuteron in Fd
Identification of $pd \rightarrow ^3\text{He}\pi^0/ ^3\text{H}\pi^+$ and $pn \rightarrow d\pi^0$

Spectator proton in STT by $dE$ vs. $E$

Deuterons, $^3\text{He}$, $^3\text{H}$ in Fd by $dE/dX$

Missing mass in $pd \rightarrow dX + p_{\text{spec}}$, $X = \pi^-$

Missing mass in $pd \rightarrow ^3\text{He} X$, $X = \pi^0$
Results of $A_y^p$ measurement

Measurement of $C_{x,x}$ and $C_{y,y}$ in $dp \rightarrow ^3\text{He}\pi^0$

Byproduct of study of $pd \rightarrow \{pp\}_s \pi^+ + p_{\text{spec}}$ at 363 MeV/A (PRC 88 (2013) 014001) and of $pd \rightarrow \{pp\}_s n$ at 600 MeV/A (EPJ A 49 (2013) 49)

- Vector polarized deuteron beam: vertical polarization $P_y = 50-60\%$, spin flipped every injection
- Hydrogen polarized internal target: vertical polarization $Q_y = 70-80\%$, Spin flipped every 5 sec

Particle detection:
- $^3\text{He}$, $^3\text{H}$ detected in $Fd$
- $\pi^+$ from $dp \rightarrow ^3\text{He}\pi^+$ in $Pd$

Polarimetry, normalization with:
- quasi-free $pn \rightarrow d\pi^0$ via $pd \rightarrow d\pi^0 + p_{\text{spec}}$
- charge-exchange $pd \rightarrow \{pp\}_s n$
- inclusive $dp \rightarrow pX$ at small $q < 60$ MeV/c
Measurements with a storage cell (1)

Polarized internal target:
atomic beam source (ABS) + storage cell + Lamb shift polarimeter

- Target thickness with the cell: $d_t = 1.34 \times 10^{13}$ cm$^{-2}$
- Cell material: 25 μm of Al + 5 μm of teflon
- Shape of background obtained from dedicated measurement with $N_2$ in the cell and with empty cell
Measurements with a storage cell (2)

- Particles identified by TOF, dE/dX
- Process identified by missing mass
- Shape of background obtained from measurements with N₂

The polarimetry process

np → dπ⁰ (via dp → dπ⁰ + p_sp)

The dp → ^3Heπ⁰ process
Results on $A_y^p$ and $A_y^d$ from dp expt. (363 MeV/A)

- Central angular region covered
- Results consistent with both J.M. Cameron et al., Nucl. Phys. A 472 (1987) 718 and ANKE pd data
- New results on $A_y^d$: abrupt change at $80^0$ related to minimum in $A_y^p$
Results on $C_{x,x}$ $C_{y,y}$ at 363 MeV/A

Observed experimental asymmetry:

$$\xi = \frac{\Sigma_1 - \Sigma_2}{\Sigma_1 + \Sigma_2}$$

$$\xi/PQ = (C_{x,x} \sin^2 \phi + C_{y,y} \cos^2 \phi),$$

where $\Sigma_1 = N \uparrow\uparrow N \downarrow\downarrow, \Sigma_2 = N \uparrow\downarrow N \downarrow\uparrow$

Fit of $\cos^2$ dependence:

- $\cos^2(\phi) = 1 \rightarrow$ get $C_{y,y}$
- $\cos^2(\phi) = 0 \rightarrow$ get $C_{x,x}$

- ANKE acceptance is best at $0^0, 180^0$ ➔ smaller errors of $C_{y,y}$
- $C_{y,y}$ changes sign at $\sim 90^0$
- $C_{y,y}(0) = -0.28 \pm 0.02 + T_{20}(0) = -1.01 \pm 0.01$ (Saclay)
  - $\cos(\phi=\text{arg}(B/A)) = 0.50 \pm 0.04, \quad \phi = 59.7^0 \pm 2.4^0$
- $C_{y,y}(180) = 0.454 \pm 0.005 + T_{20}(180) = -1.10 \pm 0.06$ (Saclay)
  - $\cos(\phi=\text{arg}(B/A)) = -0.904 \pm 0.072, \quad \phi = 154.6^0 \pm 9.6^0$
Results on $C_{x,x}$ $C_{y,y}$ at 600 MeV/A

- High background in $dp \rightarrow ^3H\pi^+$ channel
  - only $dp \rightarrow ^3He\pi^0$ is used
  - limited forward angles

- Lower statistics and beam polarization
  - large error bars

- $C_{y,y}(0) = -0.07 \pm 0.28 + T_{20}(0) = -0.66 \pm 0.02$ (Saclay)
  - $\cos(\varphi=\arg(B/A)) = 0.099 \pm 0.41$, $\varphi = 84^0 \pm 24^0$
Summary

- Proton analyzing power $A_y^p$ obtained for $pd \rightarrow ^3\text{He}\pi^0$ at 353 MeV, extending the angular range of existing data

- Spin correlation coefficients $C_{x,x}$ and $C_{y,y}$ for $pd \rightarrow ^3\text{He}\pi^0$ measured at 363 MeV/A in full range of angle

- Relative phase of spin amplitudes in the forward $\varphi = 59.7^0 \pm 2.4^0$ and backward $\varphi = 154.6^0 \pm 9.6^0$ directions calculated from ANKE $C_{y,y}$ and Saclay $T_{20}$ values

- $C_{x,x}$ and $C_{y,y}$ were measured at 600 MeV/A in the range $\Theta_\pi^{CM} = 0 - 40^0$, relative phase of spin amplitudes at $0^0$ is $\varphi = 84^0 \pm 24^0$
Additional slides
Beam polarisation and luminosity at $T_n = 353$ MeV

→ Using (quasi-) free $pp \rightarrow d\pi^+$ and $np \rightarrow d\pi^0$ $d\sigma/d\Omega$ and $A_y^p$ available from the SAID database

**Example:**
Determination of the beam polarization for $pp \rightarrow pp\pi^0$ measurement:
Consistent results $P=0.68$ from elastic and $pp \rightarrow d\pi^+$