Hyperon production in antiproton-proton annihilations with PANDA

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Outline

• Strangeness production – a probe of QCD in the confinement domain
• Strange and charmed hyperons $Y$
• Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$
  – spin $\frac{1}{2}$ hyperons
  – spin $\frac{3}{2}$ hyperons
• CP violation
• Existing data
• Prospects for PANDA
Strangeness production – a probe of QCD in the confinement domain

One of the most important questions in contemporary physics:

”What is the nature of the strong interaction in the confinement domain?”

• Light quark ($u, d$) production: non-perturbative, relevant degrees of freedom are hadrons, interactions described by Effective Field Theories.

• Scale of strangeness production $\approx m_s \approx 150$ MeV near QCD cut-off $\Lambda_{\text{QCD}} \approx 200$ MeV $\rightarrow$ relevant degrees of freedom ambiguous.

• Scale of charm production $\approx m_c \approx 1300$ MeV almost ten times larger. pQCD more relevant.

$\rightarrow$ Strangeness production probes the intermediate domain which we know very little about!
Strange and charmed hyperons

Hyperons contain one or more heavy quarks ($s, c, b$). This talk: focus on strangeness and single charm.

$SU(4)$ predicts two 20-plets.

We know that $SU(4)$ is not a good symmetry ($m_c \gg m_{s,u,d}$).

$SU(3)$ is approximately valid and the $SU(3)$ octet and decuplet are confirmed by experiment.
Strange and charmed hyperons

\[ \bar{p}p \rightarrow \bar{\Lambda}\Lambda, \ \bar{\Sigma}^{-}\Sigma^{+}, \ \bar{\Sigma}^{0}\Sigma^{0}, \ \bar{\Sigma}^{-}\Sigma^{+}, \ \bar{\Xi}^{0}\Xi^{0}, \ \bar{\Xi}^{+}\Xi^{-}, \ \bar{\Omega}^{+}\Omega^{-}, \ \bar{\Lambda}_{c}^{-}\Lambda_{c}^{+} \]

\[ p\pi^{-} \quad p\pi^{0} \quad \Lambda\gamma \quad n\pi \quad \Lambda\pi^{0} \quad \Lambda\pi \quad \Lambda K \quad \Lambda\pi \]

64% \quad 52% \quad \approx 100\% \quad \approx 100\% \quad \approx 100\% \quad \approx 100\% \quad 68\% \quad \approx 1\%

Decay weakly \( \rightarrow \) life time relatively long (\( \approx 10^{-10} \) s) \( \rightarrow \) production and decay vertices well separated.

But how are they produced?
Strangeness production – a probe of QCD in the confinement domain

Models based on the quark-gluon picture* and on the hadron picture** or a combination of the two ***

* PLB 179 (1986); PLB 165 (1985) 187; NPA 468 (1985) 669;
** PRC 31 (1985) 1857; PLB 179 (1986); PLB 214 (1988) 317;
*** PLB 696 (2011) 352.
Open questions in hyperon physics

• What are the relevant degrees of freedom?
• To what extent is SU(3) symmetry broken?
• Do all hyperons have the expected spin and parity?
• Quark structure of hyperons?
• Universe consists of matter, not antimatter. Why? CP violation needed as a part of the explanation.*

* A.D. Sakharov, JETP Lett 5 (1976)24
Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

Spin observables is a powerful tool in testing models.

In a pure ensemble the expectation value of an observable $E$ is:

$$\langle E \rangle = \langle \Psi | E | \Psi \rangle$$

where the $|\Psi\rangle$ ket describe every member of the ensemble.

Introduce an orthonormal basis $\{|a_k\rangle\}$:

$$\langle E \rangle = \langle \Psi | \left( \sum_k |\alpha_k\rangle \langle \alpha_k | \right) E | \Psi \rangle = \sum_k \langle \Psi | \alpha_k \rangle \langle \alpha_k | E | \Psi \rangle =$$

$$= \sum_k \langle \alpha_k | E | \Psi \rangle \langle \Psi | \alpha_k \rangle = \text{Tr}(E | \Psi \rangle \langle \Psi |)$$

If the density matrix is defined by $\rho \equiv |\Psi\rangle \langle \Psi |$, then $\langle E \rangle = \text{Tr}(E \rho)$. The density matrix transforms as

$$\rho_{\text{final}} = T \rho_{\text{initial}} T^\dagger$$

In case of decay of a particle with spin density matrix $\rho$, the angular distribution of the daughter particle is given by

$$I = \text{Tr}(T \rho_{\text{initial}} T^\dagger)$$
Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

The spin density matrix of a particle with arbitrary spin is given by

$$\rho = \frac{1}{2j+1} \mathcal{I} + \sum_{L=1}^{2j} \rho^L$$

with

$$\rho^L = \frac{2j}{2j+1} \sum_{M=-L}^{L} Q^L_M r^L_M$$

where $Q^L_M$ are hermitian matrices and $r^L_M$ polarisation parameters.

- Spin $\frac{1}{2}$: 3 polarisation parameters: $r_{-1}^1$, $r_0^1$ and $r_1^1$.
- Spin $\frac{3}{2}$: 15 polarisation parameters: $r_{-1}^1$, $r_0^1$, $r_1^1$, $r_{-2}^2$, $r_{-1}^2$, $r_0^2$, $r_1^2$, $r_2^2$, $r_3^3$, $r_{-2}^3$, $r_{-1}^3$, $r_0^3$, $r_1^3$, $r_2^3$ and $r_3^3$.
- Degree of polarisation given by:

$$d(\rho) = \sqrt{\sum_{L=1}^{2j} \sum_{M=-L}^{L} (r^L_M)^2}$$
Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

Spin $\frac{1}{2}$:

- The $Q_M^L$ are the Pauli matrices.
- Polarisation parameters $r_0^1$, $r_{-1}^1$ and $r_1^1$ are $P_x$, $P_y$ and $P_z$.

The spin density matrix of one spin $\frac{1}{2}$ particle is given by:

$$\rho(1/2) = \frac{1}{2} (\mathbb{1} + \vec{P} \cdot \vec{\sigma}) = \frac{1}{2} \begin{bmatrix} 1 + P_z & P_x + iP_y \\ P_x - iP_y & 1 - P_z \end{bmatrix}$$

Symmetry from parity conservation (strong production) requires $P_x = P_z = 0$, which gives:

$$\rho(1/2) = \frac{1}{2} \begin{bmatrix} 1 & iP_y \\ -iP_y & 1 \end{bmatrix}$$

Polarisation normal to the production plane!
Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

Spin $\frac{1}{2}$ hyperons:
Parity violating decay $\rightarrow$ the decay products are emitted according to the polarisation of the mother hyperon.

Angular distribution of the final state is given by $I(\theta, \varphi) = \text{Tr}(T \rho T^*)$
where $T$ is the decay matrix with one p-conserving part $T_s$ and one p-violating part $T_p$.

If one defines $\alpha = 2\text{Re}(T_s^* T_p)$
$\beta = 2\text{Im}(T_s^* T_p)$
$\gamma = |T_s|^2 - |T_p|^2$

Then $\alpha^2 + \beta^2 + \gamma^2 = 1$

it can be shown that the decay angular distribution becomes

$I(\cos\theta_p) = N(1+\alpha P Y \cos\theta_p)$

This makes the polarisation of hyperon experimentally accessible.
Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

If the decay product of the hyperon is a hyperon, e.g. $\Xi \rightarrow \Lambda K$, then also $\beta$ and $\gamma$ can be obtained from the decay protons of the $\Lambda$.

Redefine reference system such that:
- Spin of $\Xi$ along $\hat{z}$
- $p_\Lambda$ in $xz$-plane ($p_y = 0$)

Then the proton angular distribution becomes:

$$I(\theta_p, \phi_p) = \frac{1}{4\pi} \left[ 1 + \alpha_{\Xi} \alpha_\Lambda \cos \theta_p + \frac{\pi}{4} \alpha_\Lambda P \sin \theta_p (\beta_\Xi \sin \phi_p - \gamma_\Xi \cos \phi_p) \right]$$
Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$

The spin observables of the full $\bar{p}p \rightarrow \bar{Y}Y$ process can be obtained from the angular distributions of decay baryons, using

$$\rho_{\bar{B}B} = \frac{I_{Y}^{YY}}{16\pi} \sum_{\mu, \nu=0}^{3} \sum_{i, j=0}^{3} P_{i}^{\bar{p}} P_{j}^{p} \chi_{ij\mu\nu} T_{Y} T_{Y} \sigma_{\mu}^{1} \sigma_{\nu}^{2} T_{Y}^{\dagger} T_{Y}^{\dagger}$$

where $P_{j}^{p}$ is the polarisation vectors of the initial proton, and

$$\chi_{ij\mu\nu} = \frac{\text{Tr}(\sigma_{\mu}^{1} \sigma_{\nu}^{2} M \sigma_{i}^{1} \sigma_{j}^{2} M^{\dagger})}{\text{Tr}(MM^{\dagger})}$$

and

$$I_{0}^{YY} = \frac{1}{4} \text{Tr}(MM^{\dagger})$$

256 spin variables
unpol. ang. distribution

<table>
<thead>
<tr>
<th>Polarised Particle</th>
<th>None</th>
<th>Beam</th>
<th>Target</th>
<th>Both</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>$I_{0000}$</td>
<td>$A_{i000}$</td>
<td>$A_{i0j0}$</td>
<td>$A_{iij0}$</td>
</tr>
<tr>
<td>Scattered</td>
<td>$P_{0000}^{\mu0}$</td>
<td>$D_{i0\mu0}$</td>
<td>$K_{i0j0}$</td>
<td>$M_{ij\mu0}$</td>
</tr>
<tr>
<td>Recoil</td>
<td>$P_{0000}^{\nu}$</td>
<td>$K_{i00\nu}$</td>
<td>$D_{0j0\nu}$</td>
<td>$N_{ij0\nu}$</td>
</tr>
<tr>
<td>Both</td>
<td>$C_{00\mu\nu}$</td>
<td>$C_{i0\mu\nu}$</td>
<td>$C_{0ij\mu\nu}$</td>
<td>$C_{ij\mu\nu}$</td>
</tr>
</tbody>
</table>

$I$ – angular distribution
$A$ – analysing power
$P$ – polarisation
$D$ – depolarisation
$K$ – polarisation transfer
$C$ – spin correlations
$M, N$ – spin corr. tensor
Spin observables in $\bar{p}p \rightarrow YY$

The angular distribution is obtained by the trace $I_0^{BB} = \text{Tr}(\rho^{BB})$.

With an unpolarised beam and unpolarised target this becomes

$$I_0^{BB}(\Theta_Y, \hat{k}, \hat{k}) = \frac{I_0}{64\pi^3} \begin{pmatrix}
1 \\
+P_{Y,y} \bar{\alpha}k_y + P_{Y,y} \alpha k_y \\
+C_{xx} \bar{\alpha} \alpha k_x k_x \\
+C_{yy} \bar{\alpha} \alpha k_y k_y \\
+C_{zz} \bar{\alpha} \alpha k_z k_z \\
+C_{xz} \bar{\alpha} \alpha k_x k_z \\
+C_{zx} \bar{\alpha} \alpha k_z k_x
\end{pmatrix}.$$ 

$k$ being the direction vector of the decay proton.
Spin observables in $\overline{pp} \rightarrow \overline{YY}$

Spin $\frac{3}{2}$ case much more complicated.

Erik Thomé has derived the observables in his Ph. D. thesis.*

The spin density matrix is given by

$$\rho(3/2) =$$

$$\begin{bmatrix}
1 + \sqrt{3}r_0^2 & i\frac{3}{\sqrt{5}}r_{-1}^1 - \sqrt{3}r_1^2 & \sqrt{3}r_2^2 - i\sqrt{3}r_{-2}^3 & -i\sqrt{6}r_{-3}^3 \\
-i\frac{3}{\sqrt{5}}r_{-1}^1 - \sqrt{3}r_1^2 & 1 - \sqrt{3}r_0^2 & i2\sqrt{\frac{3}{5}}r_{-1}^1 + i3\sqrt{\frac{2}{5}}r_{-1}^3 & \sqrt{3}r_2^2 + i\sqrt{3}r_{-2}^3 \\
\sqrt{3}r_2^2 + i\sqrt{3}r_{-2}^3 & -i2\sqrt{\frac{3}{5}}r_{-1}^1 - i3\sqrt{\frac{2}{5}}r_{-1}^3 & 1 - \sqrt{3}r_0^2 & i\frac{3}{\sqrt{5}}r_{-1}^1 + \sqrt{3}r_1^2 \\
i\sqrt{6}r_{-3}^3 & \sqrt{3}r_2^2 - i\sqrt{3}r_{-2}^3 & -i\frac{3}{\sqrt{5}}r_{-1}^1 + \sqrt{3}r_1^2 & 1 + \sqrt{3}r_0^2
\end{bmatrix}$$

Spin observables in $\bar{p}p \to \bar{Y}Y$

$\begin{align*}
\text{Spin} & \quad \frac{3}{2} \quad \text{hyperons} \\
\text{In the case of} \quad p\bar{p} \to \Omega\bar{\Omega}, \quad \text{with the decay} \quad \Omega \to \Lambda K, \\
\text{the polarisation parameters} \quad r_2^2, \ r_1^2, \ r_0^2 \text{ can be} \\
\text{retrieved from the angular distribution of the} \ \Lambda. \\

r_0^2 &= \frac{15}{2\sqrt{3}} \left( \frac{1}{3} - \langle \cos^2 \theta_\Lambda \rangle \right) \\
r_2^2 &= \frac{8}{3} \left( 1 - \langle \cos^2 \theta_\Lambda \rangle - 2 \langle \sin^2 \theta_\Lambda \sin^2 \phi_\Lambda \rangle \right) \\
r_1^2 &= 5 \langle \cos \theta_\Lambda \sin \theta_\Lambda \cos \phi_\Lambda \rangle \\
\text{whereas the moduli of} \quad r_3^3, \ r_2^3, \ r_3^1, \ r_1^1 \text{ are} \\
\text{obtained by combining angular distribution of} \ \Lambda \\
\text{with the angular distribution of the decay proton from} \ \Lambda \to p\pi. * \\
\end{align*}$

* E. Thomé, Ph.D. Thesis, Uppsala University

and later work
The moduli of four polarisation parameters can be determined:

Assumption 1: $\alpha_\Omega = 0$, Consistent with experiment *

Assumption 2: $\beta_\Omega \approx 0$, $\gamma_\Omega \approx 1$ (not known)

CP violation in hyperon systems

• CP violation of baryon system has never been observed.
• The $\bar{pp} \rightarrow \bar{YY}$ process suitable for CP measurements (clean, no mixing)
• According to experiment, $\alpha = \bar{\alpha}$ for $\Lambda$.
• CP violation parameters:

$$A = \frac{\Gamma \alpha + \bar{\Gamma} \bar{\alpha}}{\Gamma \alpha - \bar{\Gamma} \bar{\alpha}} \approx \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

Consistent with 0 for $\Lambda$ and $\Xi$, but to confirm or rule out or confirm $\chi$PT, Supersymmetry, more precise measurements are needed.

$$B = \frac{\Gamma \beta + \bar{\Gamma} \bar{\beta}}{\Gamma \beta - \bar{\Gamma} \bar{\beta}} \approx \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}$$

Accessible for $\Xi$ since the polarisation of the decay products can be measured.

$$B' = \frac{\Gamma \beta + \bar{\Gamma} \bar{\beta}}{\Gamma \alpha - \bar{\Gamma} \bar{\alpha}} \approx \frac{\beta + \bar{\beta}}{\alpha - \bar{\alpha}}$$

No previous measurement.
Existing data on \( \bar{p}p \rightarrow \bar{Y}Y \)

- Lots of data on \( \bar{p}p \rightarrow \bar{\Lambda}\Lambda \) near threshold, mainly from PS185.
- Very few data above 4 GeV.
- Only a few bubble chamber events on \( \bar{p}p \rightarrow \Xi\Xi \).
- No data on \( \bar{p}p \rightarrow \bar{\Omega}\Omega \) nor \( \bar{p}p \rightarrow \bar{\Lambda}_c\Lambda_c \).
Existing data on $\bar{p}p \rightarrow \bar{YY}$

- Data on $P, D, K$ and $C$ for $\bar{p}p \rightarrow \Lambda\Lambda$
- $\Lambda\Lambda$ almost always produced in a spin triplet state:
  \[
  SF = \frac{1}{4} (1 + C_{xx} - C_{yy} + C_{zz})
  \]
- Neither the quark-gluon picture (dotted) nor hadron exchange (solid and dashed) describe data perfectly.
Prospects for PANDA at FAIR

- Unpolarised beam and target.
- Good vertex resolution necessary.
- For more details, see talk by E. Fioravanti, this Friday.
Prospects for PANDA at FAIR

Light hyperons ($\Lambda$, $\Sigma$):
- High event rate, low background
- Acceptance over full angular range

<table>
<thead>
<tr>
<th>Momentum [GeV/c]</th>
<th>Reaction</th>
<th>Rate [s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.64</td>
<td>$\bar{p}p \to \Lambda\Lambda$</td>
<td>580</td>
</tr>
<tr>
<td>4</td>
<td>$\bar{p}p \to \Lambda\Lambda$</td>
<td>980</td>
</tr>
<tr>
<td></td>
<td>$\bar{p}p \to \Xi^+\Xi^-$</td>
<td>30</td>
</tr>
<tr>
<td>15</td>
<td>$\bar{p}p \to \Lambda\Xi^-$</td>
<td>120</td>
</tr>
</tbody>
</table>

Results by Sophie Grape, Ph. D. Thesis, Uppsala 2009

- $\bar{p}p \to \Lambda\Lambda$
Prospects for PANDA at FAIR

Heavy hyperons: Simulation studies show high event rate and good detection efficiency over the full angular region.

Results by Erik Thomé, Ph. D. Thesis, Uppsala University (2012)

<table>
<thead>
<tr>
<th></th>
<th>$\bar{p}p \rightarrow \Xi^+\Xi^-$</th>
<th>$\bar{p}p \rightarrow \Omega^+\Omega^-$</th>
<th>$\bar{p}p \rightarrow \bar{\Lambda}_c^-\Lambda_c^+$</th>
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</thead>
<tbody>
<tr>
<td>beam momentum [GeV/c]</td>
<td>4</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>reconstruction efficiency [%]</td>
<td>17</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$\sim 2 \mu b$</td>
<td>$\sim 2$ nb</td>
<td>$\sim 0.1 \mu b$</td>
</tr>
<tr>
<td>expected # of events</td>
<td>$\sim 30$/s</td>
<td>$\sim 80$/hour</td>
<td>$\sim 25$/day</td>
</tr>
</tbody>
</table>

$\bar{p}p \rightarrow \Xi^+\Xi^-$

$\bar{p}p \rightarrow \Xi^+\Xi^-$

$\bar{p}p \rightarrow \Xi^+\Xi^-$

$\bar{p}p \rightarrow \Xi^+\Xi^-$
Prospects for PANDA at FAIR

$\bar{p}p \rightarrow \bar{\Omega}\Omega$

$\bar{p}p \rightarrow \bar{\Lambda}_c\Lambda_c$

Results by Erik Thomé, Ph. D. Thesis, Uppsala University (2012)
Prospects for PANDA at FAIR

CP violation:

• Measurable in $\Lambda$ and $\Xi$ decay
• Particle ID requirement gives systematic bias – better measure without ID
• Only tracks near the beam pipe should be considered.

Results by Erik Thomé, Ph. D. Thesis, Uppsala University (2012)
Summary

• Hyperon production is a probe of the Strong Interaction in the confinement domain.

• CP violation measurements of hyperon systems provide a clean test of e.g. physics beyond the Standard Model.

• Spin observables of the $p\bar{p} \rightarrow \Omega \bar{\Omega}$ process recently derived by the Uppsala group.

• Simulation studies by the Uppsala group show excellent prospects for ALL antihyperon-hyperon channels with PANDA:
  – High event rate
  – Low background
  – Good detection efficiency over the full phase space

Thanks to: Sophie Grape, Tord Johansson and Erik Thomé