Future Spin Observables Measurements with the \PANDA Detector at FAIR

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Abstract. Hyperon production in $pp \to \bar{Y}Y$ reactions is one of the main parts of the \PANDA physics program. By colliding antiprotons and protons with HESR at FAIR, antihyperon hyperon pairs can be produced via the annihilation of light antiquark quark pairs and the production of $s\bar{s}$ pairs. Feasibility studies have been performed for a set of $pp \to \bar{Y}Y$ reactions. Reconstruction rates for these reactions at \PANDA have been estimated. In particular, the feasibility of measuring spin observables in the $pp \to \Xi^+ \Xi^-$ reaction at $p_{beam} = 7.0$ GeV/c is presented.

1. Introduction

The Standard Model of particle physics is the theory that describes the electromagnetic, weak and the strong interaction. Within it, quantum chromodynamics (QCD) is the field theory that describes the interaction between quarks, mediated by gluons. While perturbation theory can be successfully employed to perform predictions at high energies and short distances, it cannot be employed at lower energies and hadronic scales. This is due to the fact that the strong coupling constant $\alpha_s$ grows large at low energies. In these cases, effective field theories such as Chiral Perturbation Theory ($\chi$PT) can be used. Here, hadrons act as the degrees of freedom. Strangeness production, however, occurs at an energy scale where the degrees of freedom are unclear. Experiments on hyperon production in $pp \to \bar{Y}Y$ reactions provide a clean environment for studying the production mechanism. Predictions on single strangeness production have been done with phenomenological models based on quark-gluon degrees of freedom [1], kaon exchange [2], as well as a mix of the two [3]. Predictions have also been done in the double-strange sector [4, 5, 6]. The PS185 collaboration has measured large, high-quality samples of single-strange hyperons in $pp \to \bar{Y}Y$ reactions [7]. However, no model has completely described the spin structure of the reactions. Furthermore, the models treating the double-strange sector have not been tested as the amount of data on double-strange hyperon production in $pp \to \bar{Y}Y$ is scarce. The \PANDA (antiProton ANnihilation at DArmstadt) experiment at FAIR (Facility for Antiproton and Ion Research) will open the possibility to not only provide improved measurements in the single-strange sector, but also provide new measurements in the double-strange sector. Various $\bar{p}p \to \bar{Y}Y$ reactions will be exclusively reconstructed and, by measuring spin observables, a better understanding of the production mechanism will be achieved.
2. Spin observables in $\bar{p}p \to YY$ Reactions

The spin variables for the $\bar{p}p \to YY$ reaction are derived using the density matrix formalism [8]. The derivation starts by considering the density matrix of the initial $\bar{p}p$ system

$$\rho_{\bar{p}p} = \frac{1}{16\pi} \sum_{i,j=0}^{3} P^p_i P^p_j \sigma^p_i \sigma^p_j,$$

(1)

where $P^p_i$, $P^p_j$ denote the polarization of the incident antiproton and target proton, respectively, and $\sigma^p_i$, $\sigma^p_j$ are Pauli matrices. The density matrix of the $YY$ system is obtained by transforming the $\bar{p}p$ density matrix $\rho_{\bar{p}p} = M \rho_{\bar{p}p} M^\dagger$. A complete explanation of this step is found in [9]. The density matrix of the $YY$ system is then

$$\rho_{YY} = \frac{I_{YY}^0}{16\pi} \sum_{i,j=0}^{3} \sum_{\mu,\nu=0}^{3} P^p_i P^p_j \chi_{ij\mu\nu} \sigma^1_{\mu} \sigma^2_{\nu},$$

(2)

where $I_{YY}^0$ is the differential cross section and $\chi_{ij\mu\nu}$ are the spin observables. Assuming that the hyperons decay weakly, the angular distribution of the decay particles can be obtained. The angular distribution of $\bar{p}p \to YY \to B\pi^+\pi^-$, where $B$ is the daughter baryon and $Y \to B\pi$, is obtained by first defining the production plane in the center-of-mass frame. In Figure 1 (a), the production plane for the $\bar{p}p \to \Xi^+\Xi^-$ reaction is shown. Furthermore, the decay frames of the hyperons, shown in Figure 1 (b), are defined such that the $y$-axes are perpendicular to the production plane and the $z$-axes point in the direction of movement of the respective hyperon. The opening angles $\cos \theta_{\mu} \equiv k_{\mu}$ are spanned by the $\mu$-axis and the direction of the outgoing baryon $B$. With the reference frames defined, the angular distribution of the outgoing baryons

Figure 1. (a) Production plane of the $\bar{p}p \to \Xi^+\Xi^-$ reaction. The $y$-axes are perpendicular to the production plane. (b) The $\Xi^+ \to \Lambda\pi^+$ decay frame.

is obtained by taking the trace of the density matrix $I = \text{Tr}(T\rho T^\dagger)$, where the $T$ matrices describe the $Y \to B\pi$ decays and contain both a parity conserving $P$ and parity violating $S$ amplitudes. [9]. This yields

$$I(\vec{\kappa}_\mu, k_\nu) = \frac{I_{YY}^0}{64\pi^3} \sum_{i,j=0}^{3} \sum_{\mu,\nu=0}^{3} \pi \alpha P^p_i P^p_j \chi_{ij\mu\nu} \vec{\kappa}_\mu k_\nu,$$

(3)

where $\vec{\pi}$ and $\alpha$ are the decay asymmetry parameters of the $Y$ and $Y$ hyperons, respectively, and $\vec{\kappa}_\mu$ and $k_\nu$ are the opening angles with respect to the polarization axes $\mu$ and $\nu$, respectively. In
total, there are 256 spin observables. They are summarized in Table 1. At PANDA, unpolarized beam and target will be used. Thus, the accessible spin observables are the polarizations \( P_{0000} \equiv P_Y^0 \), \( P_{0000} \equiv P_Y^0 \), and the spin correlations \( C_{0000} \equiv C_{\mu\nu} \). The normalized angular distribution then becomes

\[
I(\kappa_{\mu},k_{\nu}) = \frac{1}{16\pi^2} \left( 1 + \alpha \sum_{\mu} P_{\mu}^Y \kappa_{\mu} + \alpha \sum_{\nu} P_{\mu}^Y k_{\nu} + \alpha \alpha \sum_{\mu,\nu} C_{\mu\nu} \kappa_{\mu} k_{\nu} \right).
\]

(4)

Since the \( pp \rightarrow YY \) reaction is mediated by the strong interaction, it must be invariant under rotation and parity. These constraints imply \( P_Y^x = P_Y^z = P_Y^x = P_Y^z = 0 \), \( C_{xy} = C_{yx} = C_{yz} = C_{zy} = 0 \), \( P_Y^y = P_Y^y \), and \( C_{xx} = C_{xx} \). If the symmetric spin correlations are measured, then the singlet fraction \( F_S \) also becomes accessible. It is defined as

\[
F_S = \frac{1}{4}(1 + C_{xx} - C_{yy} + C_{zz}).
\]

(5)

By measuring \( F_S \), it can be deduced whether the \( YY \) pair is produced in a singlet state (antiparallel spin), triplet state (parallel spin), or if the spins are uncorrelated. It has values of

\[
F_S = \begin{cases} 
0 & \text{for a pure triplet state} \\
1 & \text{for a pure singlet state} \\
\frac{1}{4} & \text{for uncorrelated spin directions.}
\end{cases}
\]

(6)

3. The PANDA Experiment at FAIR

The PANDA detector is a general purpose fixed-target spectrometer that will be located at the future accelerator complex FAIR at GSI, Germany. The High Energy Storage Ring (HESR) will provide an antiproton beam in a momentum range of 1.5–15 GeV/c. In the High Luminosity operation mode, a luminosity of \( 2 \cdot 10^{32} \text{ cm}^{-2} \text{s}^{-1} \) will be provided. During the starting phase of PANDA, a luminosity of around \( 10^{31} \text{ cm}^{-2} \text{s}^{-1} \) will be available, depending on the beam momentum.

4. Selected Results

Simulation studies have been performed with the PandaRoot software package [10] to test the feasibility of measuring spin observables in various \( pp \rightarrow YY \) reactions. The \( pp \rightarrow \Lambda \bar{\Lambda} \) reaction has been studied at a beam momentum of \( p_{\text{beam}} = 1.64 \text{ GeV/c} \). This reaction serves as a benchmark reaction for the PANDA experiment as it is the most extensively studied reaction.
The $\bar{p}p \rightarrow \Sigma^0\Lambda$ reaction has been studied at beam momenta of $p_{\text{beam}} = 1.771$ GeV/c and $p_{\text{beam}} = 6.0$ GeV/c. The lower beam momentum was chosen as it lies below the $\bar{p}p \rightarrow \Sigma\Sigma$ threshold, thus removing a significant background channel. The higher beam momentum was chosen as it is the highest energy where the differential cross section has been previously measured. The beam momenta for the $\bar{p}p \rightarrow \Xi^+\Xi^-$ reaction was chosen at $p_{\text{beam}} = 4.6$ GeV/c and $p_{\text{beam}} = 7.0$ GeV/c. The feasibility studies can be divided into two components: the exclusive reconstruction of the whole reaction chain together with a signal-to-background ratio of $S/B \sim 100$, and input-output checks of reconstructed spin observables. The event selection revolves around the reconstruction of displaced vertices and constraints to the initial system using kinematic fits. Selection criteria are applied on kinematic fit probabilities, invariant mass distributions of hyperons, distance between displaced vertices and the interaction point. In the $\bar{p}p \rightarrow \Sigma^0\Lambda$ case, additional selection criteria are applied on photon energy deposits. The resulting reconstruction rates are summarized in Table 2.

Table 2. Preliminary results on reconstruction rates of $\bar{p}p \rightarrow YY$ reactions given the lowest estimate of starting luminosity of PANDA.

| Momentum (GeV/c) | Reaction            | $\sigma$ (µb) | Efficiency (%) | Rate (s$^{-1}$) |
|-----------------|---------------------|--------------|----------------|-----------------|
| 1.64            | $\bar{p}p \rightarrow \Lambda\Lambda$ | 64           | 15.7           | 10              |
| 1.771           | $\bar{p}p \rightarrow \Sigma^0\Lambda$ | 11           | 5.3            | 0.6             |
| 6.0             | $\bar{p}p \rightarrow \Sigma^0\Lambda$ | 20           | 6.1            | 1.6             |
| 4.6             | $\bar{p}p \rightarrow \Xi^+\Xi^-$         | ~1           | 8.2            | 0.1             |
| 7.0             | $\bar{p}p \rightarrow \Xi^+\Xi^-$         | ~0.3         | 7.9            | 0.03            |

In addition to feasibility studies regarding the reconstruction of $\bar{p}p \rightarrow YY$ reactions, input-output studies have been performed for the $\bar{p}p \rightarrow \Lambda\Lambda$ and $\bar{p}p \rightarrow \Xi^+\Xi^-$ reactions. Here, results on the $p_{\text{beam}} = 7.0$ GeV/c case are presented. At the event generation level, the $\bar{p}p \rightarrow \Xi^+\Xi^-$ reaction, where $\Xi \rightarrow \Lambda\pi$ and $\Lambda \rightarrow p\pi$, is simulated based on an input model where the polarization is set to $P^Y = P^Y = \sin 2\theta_{\text{cm}}$, and $C_{xx} = C_{yy} = C_{zz} = C_{xz} = C_{zx} = \sin \theta_{\text{cm}}$. Generated events are propagated through the PandaRoot analysis chain. The $\Xi$ hyperons are reconstructed by testing all combinations of protons and pions. The Decay Chain Fitting package [12] is used to reconstruct both the $\Xi$ and the $\Lambda$ hyperon decay vertices while simultaneously imposing a mass constraint on the $\Lambda$. The $\Xi^+\Xi^-$ hyperons are combined to form the initial system. Topological selection criteria where $z(\Lambda) > z(\Xi)$ and the opening angle $\angle(\Xi^+\Xi^-) > 3$ rad are also imposed. The $\Lambda\pi$ invariant masses are required to be within $\pm15$ MeV/c$^2$ of the $\Xi$ mass peak at 1322 MeV/c$^2$. Finally, the sum of the $\Xi$ hyperon $z$-positions are required to be larger than 3 cm. Out of the generated $8.5 \cdot 10^5$, $6.76 \cdot 10^4$ reactions are reconstructed, resulting in a reconstruction efficiency of $\epsilon = 7.91\%$.

After the event selection, the spin observables are reconstructed. The Method of Moments is used to extract the polarization and spin correlation from the angular distribution according to Equation (4). A two-dimensional acceptance correction is performed for the extraction of polarization, and a three-dimensional acceptance correction is used to extract the spin correlations. The reconstructed polarizations of the $\Xi^+$ and $\Xi^-$ hyperons are averaged as they are constrained to be equal. The resulting polarization is shown in Figure 2 (a). From the

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1 Results on $\bar{p}p \rightarrow \Sigma^0\Lambda$ were produced by G Pérez [11].
reconstructed spin correlations \( C_{xx}, C_{yy}, C_{zz}, \) the singlet fraction is calculated according to Equation (5). The resulting singlet fraction is shown in Figure 2 (b).

Both the reconstructed polarization and singlet fraction are in good agreement with the input model. The event sample used can be collected within 24 days of data taking given the conservative estimate of the starting phase luminosity of PANDA. The same data sample could be collected within a day once the High Luminosity mode of PANDA is available.

5. Summary and Outlook

Feasibility studies have been performed for the \( pp \rightarrow \Xi^+\Xi^- \), \( pp \rightarrow \Lambda \Lambda \), \( pp \rightarrow \Sigma^0 \Lambda \), and the \( pp \rightarrow \Xi^+\Xi^- \) reactions. Satisfactory reconstruction efficiencies have been achieved, enabling the study of spin observables already during the starting phase of PANDA. In addition, the feasibility of measuring the polarization \( P_y \) and the singlet fraction \( F_S \) in the \( pp \rightarrow \Xi^+\Xi^- \) reaction has been studied. The reconstructed \( P_y \) and \( F_S \) are found to be in good agreement with the input model, given a beam time of 24 days with the most conservative estimate of the luminosity. This work was supported by the Swedish Research Council grant VR 2013-04278 and the Knut and Alice Wallenberg Foundation grant 2016.0157.

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