Measurement of Spin Observables in Exclusive $\bar{p}p \rightarrow \Lambda\Lambda$ Production

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The PS185 experiment at LEAR has produced a wealth of high precision measurements of cross-sections and final-state polarization observables in near-threshold antihyperon-hyperon production from antiproton-proton annihilation. In its most recent run, PS185/3 extended its capabilities by utilizing a transversely polarized frozen-spin target to measure exclusive $\Lambda\Lambda$ production. This allows direct access to a broad set of spin observables involving initial-state spin. Competing theoretical models for this reaction have differing predictions for some of these newly-accessible spin observables, most notably the depolarization $D_{nn}$. Results for these observables are expected to be useful in distinguishing these models. In addition, this data can be used to determine the parameters of the spin scattering matrix, providing a complete description of the spin structure of the reaction. Preliminary results are presented. These results are in direct conflict with current predictions and present an intriguing invitation for future theoretical work.
Introduction

The exclusive production of antihyperon-hyperon states from antiproton-proton annihilation ($\bar{p}p \rightarrow \bar{Y}Y$) has been extensively studied near threshold by the PS185 collaboration throughout the lifetime of LEAR. Results for the total and differential cross-sections and for those spin observables depending only on final-state spins have been published for a range of energies and channels. Most of this data has been in the $\Lambda\Lambda$ production channel, which has been explored from very near threshold to a center of mass excess energy of about 200 MeV.

Both t-channel meson exchange models and s-channel constituent quark models have been applied to interpret this data, with both approaches providing a reasonable description of the current data. One reason for this is uncertainty in the $\bar{Y}Y$ final-state interaction (FSI). The freedom in the FSI parameters, and to a lesser extent in the initial-state interaction parameters, may obscure the effects of the strangeness production model. This problem is reduced when considering observables that depend on the initial-state spin. Specifically, the two models give very different predictions for the depolarization $D_{nn}$ [1,2]. $D_{nn}$ measures the correlation between the initial-state proton spin and the $\Lambda$ spin in the direction normal to the scattering plane. Meson exchange calculations, having a dominant tensor force, have predicted a strongly negative $D_{nn}$, while quark model calculations have predicted a positive $D_{nn}$. These predictions are insensitive to the FSI and ISI, so measurement of this observable provides a sensitive test that can be used to distinguish these models [1,2]. The depolarization is also significant to models, motivated by the proton spin puzzle, that are based on intrinsic polarized strangeness in the nucleon [3,4].

For this reason, the PS185 collaboration modified its apparatus to include a transversely polarized proton target [5,6]. Data was taken in 1996 at beam momenta of 1525 MeV/c and 1640 MeV/c. Some preliminary results from the analysis of the 1640 MeV/c data set are presented here.

Experiment

A schematic representation of the detector is shown in fig. 1. A more detailed description of the experimental set-up can be found in ref. [7]. The PS185 detector recorded the tracks from the charged mode of hyperon decay. The boost to the lab frame confines the $\bar{Y}Y'$ production reaction to a forward cone, so a detector in the forward region provided $4\pi$ c.m.s. coverage for detection of the hyperons. Wire chambers were used to track the hyperon decay products. The event topology was then fit to a kinematic hypothesis for the exclusive $\Lambda\Lambda$ production. The statistical quality of this fit provides the primary quality criteria for each event. This technique was restrictive enough to not only exclude other final states, but also to exclude almost all quasi-free production from non-hydrogen nuclei. Behind these wire chambers, three drift planes in a magnetic field detected deflection of the decay particle tracks in order to distinguish the $\Lambda$ from the $\bar{\Lambda}$. For the trigger, scintillators were placed directly upstream and downstream of the target to detect incoming beam particles while vetoing charged particles exiting the target. A hodoscope placed behind the tracking chambers detected the charged final state. These three components were combined to create a simple charge-neutral-charge trigger arrangement. In order to maintain the trigger efficiency, it was crucial to place the veto scintillators as close as
possible to the target. A frozen-spin butanol target [6] with a outer cryostat diameter of only 4.2 cm was used, which allowed close placement of the veto counters. The average polarization of the target during the run period was about 62%.

**Preliminary Results**

The self-analyzing weak decay of the hyperon correlates the direction of the decay products with the hyperon spin. This allows measurement of the spin observables of the production reaction simply by measuring the angular distribution of the decay products. Without target or beam polarization, the decay distribution for any production angle depends on only 5 spin observables: $P_{n3}, C_{mn}, C_{nn}, C_{lt},$ and $C_{mt}$. These observables refer to a frame in which $\hat{n}$ is the normal to the scattering plane, $\hat{l}$ is different for each particle and points in the direction of the particle's c.m.s. motion, and $\hat{m} = \hat{n} \times \hat{l}$. $\hat{m}$ and $\hat{l}$ point in opposite directions for the anti-hyperon and hyperon, as indicated in fig. 2. For the measurement with a polarized target, we introduce a similar frame for the target proton: $\hat{n}$ is the normal to the scattering plane, $\hat{l}$ is the direction of the proton momentum in the c.m.s. frame, and $\hat{m} = \hat{n} \times \hat{l}$. By construction, a transverse target polarization has no component in the $\hat{l}$ (longitudinal) direction, so spin observables involving the $\hat{l}$ direction of the proton spin cannot be directly measured by this experiment.

Many spin observables are restricted to be zero or have trivial relationships with other observables due to parity or $C$-parity symmetries. Taking these symmetries into account, the angular distribution for the PS185/3 data taken with a transversely polarized target depends on 19 non-zero spin observables that are not trivially related. It can be written
Figure 2. Definition of coordinate axes used to describe the spin observables for $\bar{p}p \rightarrow \Lambda\Lambda$.

in this form:

$$I_{\bar{p}p}(\theta, \phi, \hat{k}_1, \hat{k}_2) = \frac{I_{\Lambda\Lambda}(\theta)}{32\pi^3} \left( 1 + P_n(\theta) (\hat{\alpha}k_{1n} + \alpha k_{2n}) + C_{00n}(\theta) \hat{\alpha}\alpha k_{1n} k_{2n} + C_{00mn}(\theta) \hat{\alpha}\alpha k_{1m} k_{2n} + C_{00nl}(\theta) \hat{\alpha}\alpha k_{1n} k_{2l} + C_{00nl}(\theta) \hat{\alpha}\alpha k_{1m} k_{2l} + C_{11}(\theta) (P_T \cos \phi + \hat{\alpha}\alpha P_T k_{1n} k_{2n} \cos \phi) + K_{mn}(\theta) \alpha P_T k_{1n} \cos \phi + D_{nn}(\theta) \alpha k_{1m} \cos \phi + K_{mm}(\theta) \hat{\alpha} k_{1l} \sin \phi + K_{ml}(\theta) \alpha P_T k_{1l} \sin \phi + D_{mm}(\theta) \alpha k_{2n} \sin \phi + D_{ml}(\theta) \alpha P_T k_{2l} \sin \phi + C_{01mn}(\theta) \hat{\alpha}\alpha P_T (k_{1m} k_{2n} \cos \phi - k_{1l} k_{2l} \cos \phi) + C_{01nl}(\theta) \hat{\alpha}\alpha P_T k_{1m} k_{2l} \cos \phi + C_{01nm}(\theta) \hat{\alpha}\alpha P_T k_{1l} k_{2m} \cos \phi + C_{01ml}(\theta) \hat{\alpha}\alpha P_T k_{1l} k_{2l} \sin \phi + C_{01ln}(\theta) \hat{\alpha}\alpha P_T k_{1m} k_{2n} \sin \phi + C_{01mm}(\theta) \hat{\alpha}\alpha P_T k_{1n} k_{2m} \sin \phi + C_{01ml}(\theta) \hat{\alpha}\alpha P_T k_{1n} k_{2l} \sin \phi \right)$$

(1)

Here $\hat{k}_1$ and $\hat{k}_2$ are the directions of the decay $\bar{p}$ and proton, and $\hat{\alpha}$ and $\alpha$ are the weak decay asymmetry parameters for the $\Lambda$ and $\Lambda$ decays. The azimuthal production angle $\phi$ is measured from the normal to the scattering plane to the target polarization direction. $P_T$ is the magnitude of the target polarization, $I_0$ is the differential cross-section for the $\Lambda\Lambda$ production reaction, and $I_0$ and each spin observable is a function of the polar production angle $\theta$.

The observables in each term of eqn. (1) are not completely independent, as each can be written in terms of the parameters of the spin scattering matrix. In the spin scattering matrix formalism, the transition matrix is composed of all possible combinations of spin operators that do not violate the discrete symmetries of the reaction [8]. For $\bar{p}p \rightarrow \Lambda\Lambda,$
this matrix can be written in this form, with only 6 complex (11 real) parameters:

\[
\mathcal{M}_{\bar{p}p \rightarrow \Lambda \bar{\Lambda}} = \frac{1}{2} \begin{pmatrix}
(a + b) & (a - b) \\
+ & + \\
(c + d) & (c - d) \\
+ & + \\
e & (e + f) \\
+ & + \\
&
\end{pmatrix}
\sigma_1 \cdot \hat{n} \sigma_2 \cdot \hat{n} \\
\sigma_1 \cdot \hat{m} \sigma_2 \cdot \hat{m} \\
\sigma_1 \cdot \hat{l} \sigma_2 \cdot \hat{l} \\
\sigma_1 \cdot \hat{m} + \sigma_2 \cdot \hat{n} \\
\sigma_1 \cdot \hat{m} \sigma_2 \cdot \hat{l} \nonumber
\]  

(2)

Here \( \sigma \) are the Pauli spin matrices. The parameters \( \{a..f\} \) are functions of production angle \( \theta \) and contain all non-spin-related dependence of the reaction. Each spin observable can now be written, with \( \sigma_0 \) being the identity matrix, as:

\[
X_{ij\mu\nu} = \frac{1}{4I_0} Tr \left[ \sigma_{ij} \sigma_{\mu\nu} \mathcal{M} \mathcal{M}^\dagger \right]
\]  

(3)

\( X_{ij\mu\nu} \) is a generalized notation for all spin observables for this reaction, such as those in eqn. (1). Eqn. (3) leads to a large number of non-trivial relationships between the spin observables [9]. Any method for extracting this set of spin observables that does not account for these relationships fails to maximize the statistical value of the results, and does not correctly handle the covariances between the observables.

It has recently been demonstrated that the spin scattering matrix parameters can be uniquely determined from this set of 19 non-zero spin observables [10]. This implies that, in principle, a direct fit of these parameters can be performed. This fit would maximize the statistical significance of the results, correctly measure the covariance between spin observables, and provide results that are physically allowable under the spin scattering matrix formalism. These are all areas in which other methods for extraction of spin observables fall short. In addition, the results of this fit would then allow the entirely model independent calculation of the conventional spin observables, not only for those 19 spin observables that can be directly measured with a transversely polarized target, but for all spin observables associated with the \( \bar{p}p \rightarrow \Lambda \bar{\Lambda} \) reaction.

This fit has been performed. The data is binned in the cosine of the production angle \( \cos \theta_{em} \), and in each bin an un-binned fit is performed over the remaining variables of the angular distribution. The results of the fit are values for the 11 real parameters of the spin scattering matrix. Using these parameters, results for spin observables are calculated in an entirely model-independent way. While the transition matrix parameters are the most complete and minimal presentation of the results of this analysis, it is currently the results for individual spin observables that generate the most interest. For this reason, the spin observables will be presented here. It should be noted that future theoretical calculations would be best compared to the transition matrix parameters themselves, rather than to the highly inter-related spin observables. Results for these parameters are not presented here, but will be included in a future publication. For all of the spin observable results shown here, the 1\( \sigma \) uncertainty limits have been determined by means of an exhaustive search of the log-likelihood surface that maps out the uncertainty range for each observable.

There are 5 spin observables that can be measured without target or beam polarization. For those observables, there is good agreement between the current analysis and a previous:
Figure 3. Previous and current results for the polarization $P_\pi$, and singlet fraction $S_f$ for $\bar{p}p \rightarrow \Lambda\Lambda$. The previous results are from [11].

Figure 4. The depolarization $D_{nn}$, and polarization transfer $K_{nn}$ for $\bar{p}p \rightarrow \Lambda\Lambda$. Meson exchange model predictions are from [1], while quark model predictions are from [2]. Both predictions include effects from initial- and final-state interactions.

measurement [11], which serves to demonstrate that the systematics of the current analysis are well controlled. The results for the $\Lambda$ and $\bar{\Lambda}$ polarization $P_\pi$ and the singlet fraction $S_F$ are shown in fig. 3. The singlet fraction is a linear combination of the spin correlation coefficients between the $\Lambda$ and the $\bar{\Lambda}$, $S_F = \frac{1}{4}(1 + C_{nm} - C_{nn} + C_{n\bar{d}})$. $S_F = 0$ would indicate that the $\Lambda$ and $\bar{\Lambda}$ are always produced in a triplet configuration, while $S_F = 0.25$ would imply a statistical mixture of single and triplet final states. Although it is widely noted that previous PS185 measurements have found a singlet fraction very near zero, that is, a dominance of $\Lambda\Lambda$ triplet-state production, it is sometimes overlooked that at backward production angles, the singlet contribution becomes significant. One can see that the new results confirm this behavior, seen in the previous measurement.

The depolarization $D_{nn}$ and the polarization transfer $K_{nn}$ were the primary focus of the
PS185/3 measurement. The polarization transfer, which is a measure of the target proton spin transfer to the \( \Lambda \), is analogous to the depolarization, which is a measure of the target proton spin transfer to the \( \Lambda \). The different models of strangeness production produce differing predictions for both \( K_{nn} \) and \( D_{nn} \). The preliminary results for \( K_{nn} \) and \( D_{nn} \) are shown in fig. 4, with the predictions [1,2] superimposed. Clearly, the predictions from both models are inconsistent with the results for these observables. This demonstrates that the dynamics of strangeness production are not well understood.

Future improvements in our theoretical understanding of this reaction may now be guided by much more information than was previously available. While the original intent of the PS185/3 measurement was to distinguish between alternative models of the production mechanism by measuring the depolarization \( D_{nn} \), the results of this analysis extend far beyond that goal.

Taking into account the discrete symmetries of the reaction, there are a total of 39 spin observables that are not trivially related. The direct measurement of this full set of observables variously requires beam and target polarizations, both transverse and longitudinal. However, each of these observables can be calculated from the parameters of the spin scattering matrix in an entirely model-independent way. Thus the current analysis, which measures the spin scattering matrix parameters, represents a complete measurement of the spin structure of the reaction. Examples of results for several observables that can be directly measured are presented in fig. 5. Examples of results for two spin observables that can not be directly measured using a transversely polarized target are shown in fig. 6.
Figure 6. Two elements completing the polarization transfer tensor: $K_u$ and $K_{im}$. These observables measure the correlation between the longitudinal target polarization and specific components of the $\Lambda$ polarization. They cannot be directly measured using only a transverse target polarization, but their values can be indirectly determined from the results for the spin scattering matrix parameters.

These results should still be considered preliminary. Consideration must be given to potential sources of systematic error such as production off carbon nuclei in the target, but these are expected to have little effect on the presented results. The systematic uncertainty must be estimated before these results can be considered final. Finally, it should be noted that the second data set, taken with a beam momentum of $1525 \, \text{MeV/c}$, is still under analysis at the University of New Mexico, Albuquerque.

REFERENCES